

Experimental review of results on charmonium-like states

Frank Nerling
HFHF, GSI Darmstadt

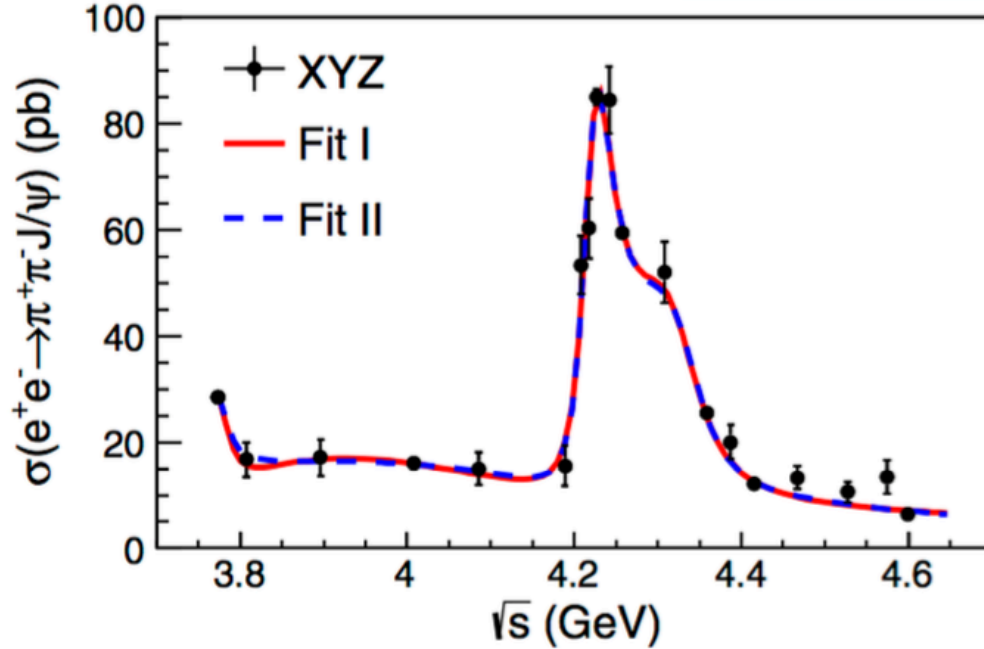
MESON2021, May 17th - 20th 2021

Outline

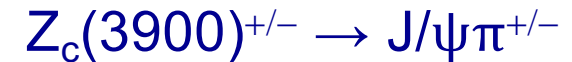
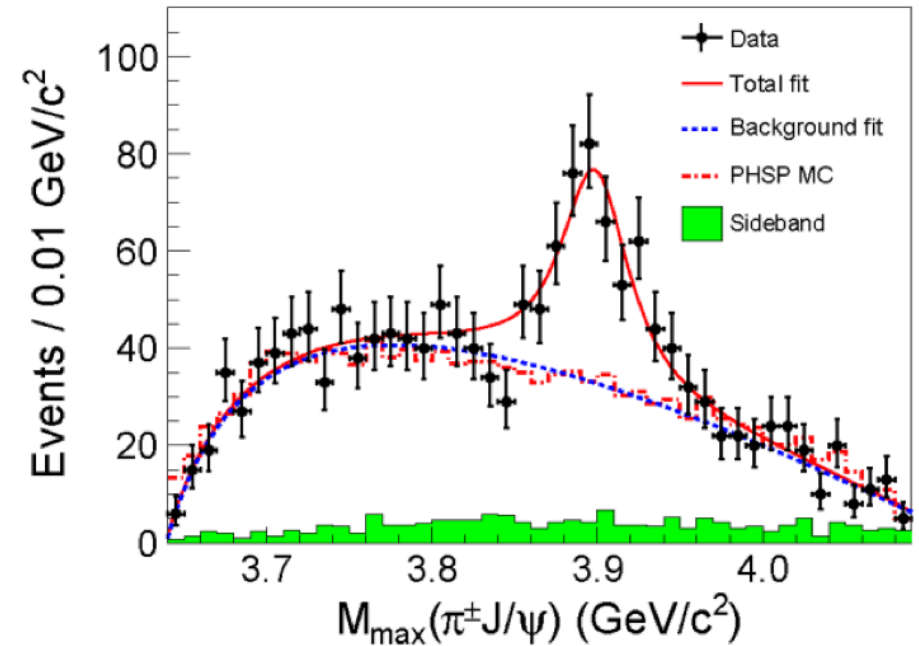
- **Introduction**
- **The role of e^+e^- annihilation**
- **A selection of famous and recent results**
 - Supernumerary vector Y states
 - Manifestly exotic Z_c states
 - The $X(3872)$ and other X states
- **Summary**

Famous exotic (?) XYZ states

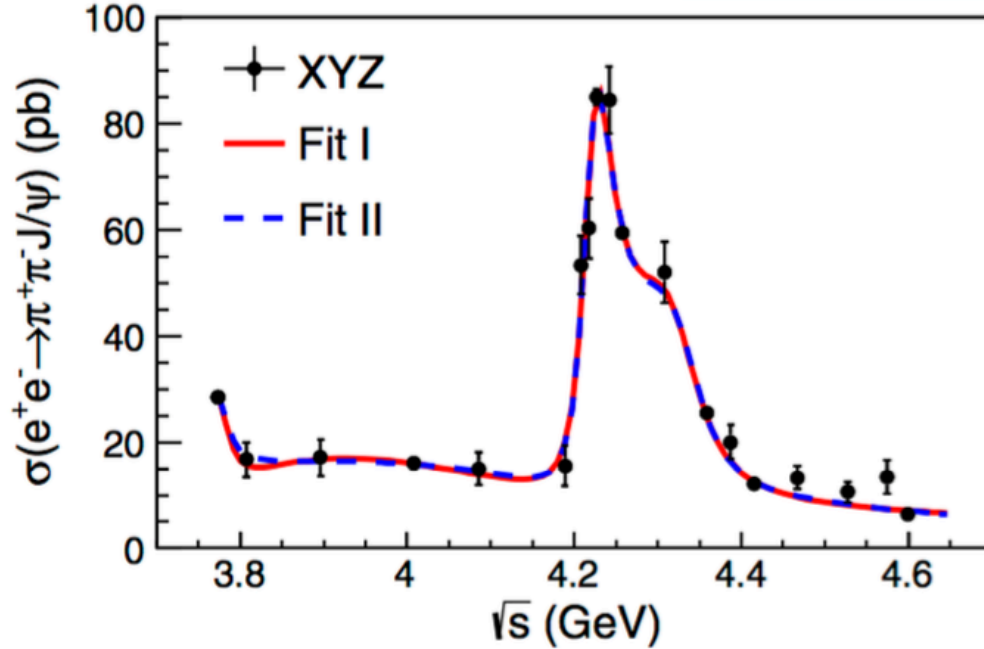
[PRL 118 (2017) 092001]



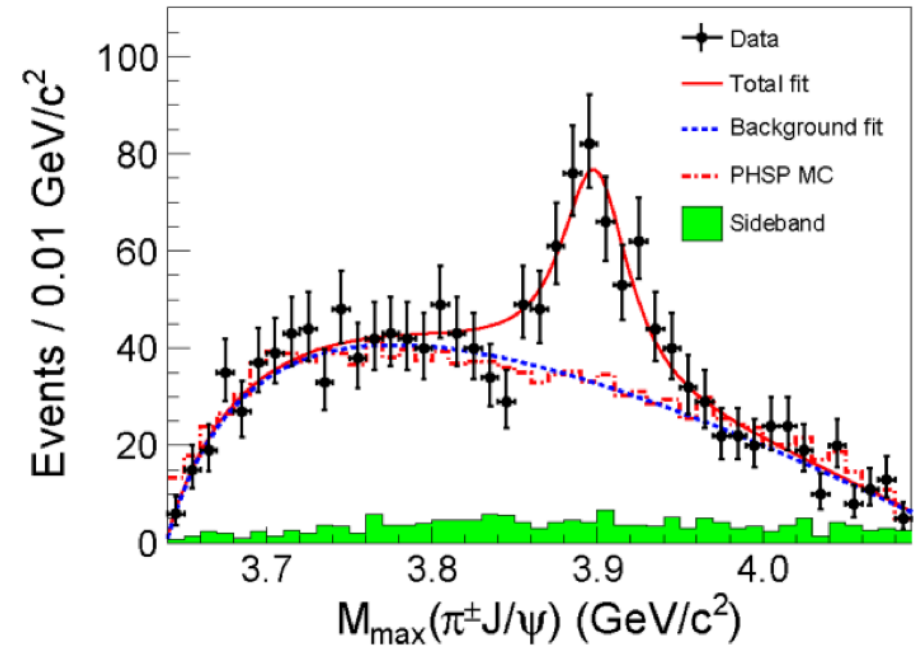
[PRL 110 (2013) 252001]



[PRL 118 (2017) 092001]

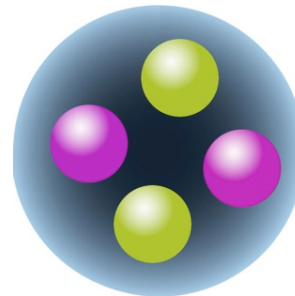


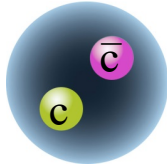
[PRL 110 (2013) 252001]



$$Y(4260) \rightarrow J/\psi \pi^+ \pi^-$$

$$Z_c(3900)^{+/-} \rightarrow J/\psi \pi^{+/-}$$





Potential model:

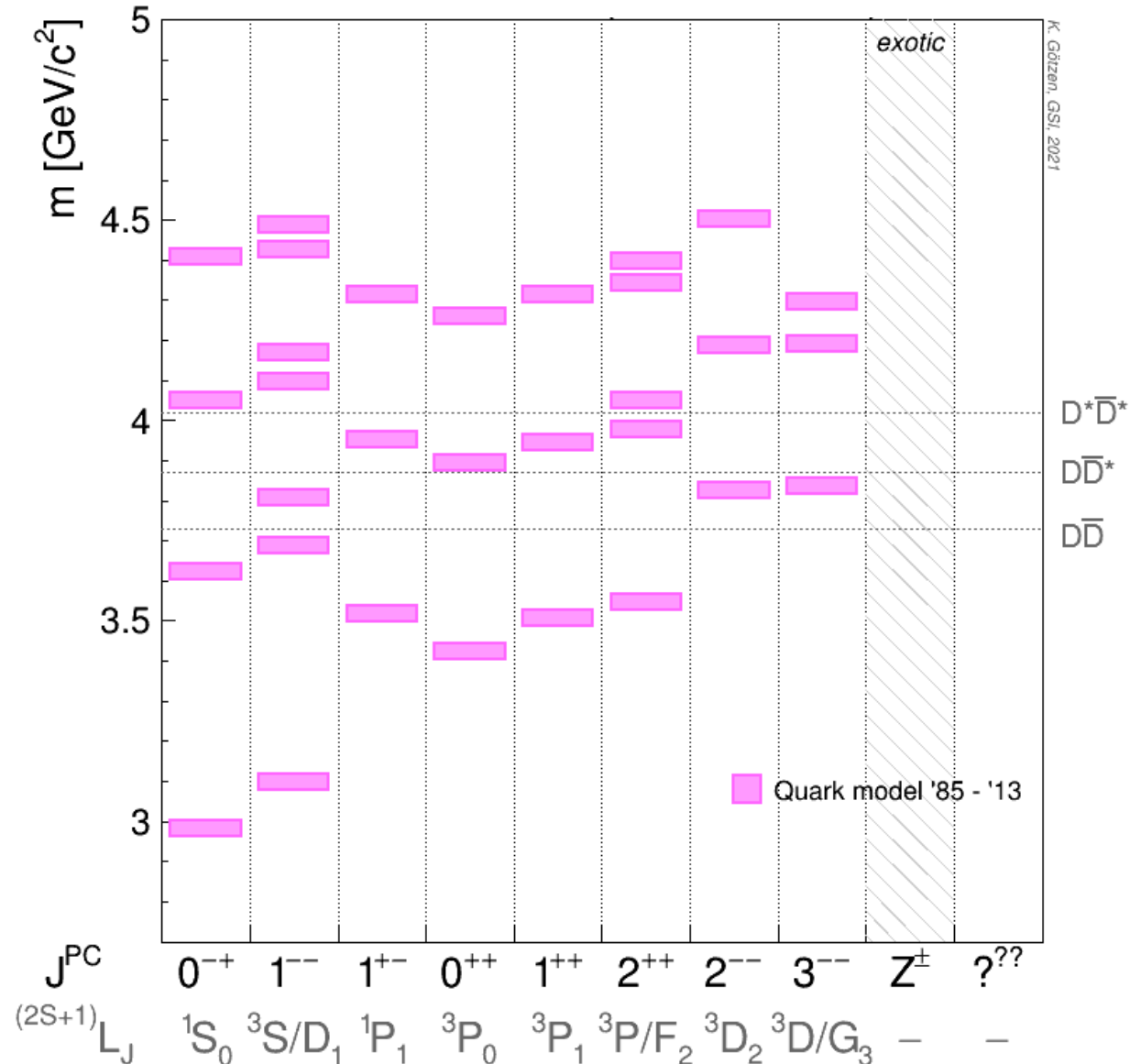
$$V_0^{c\bar{c}} = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2} \delta(r) \vec{S}_c \vec{S}_{\bar{c}}$$

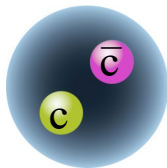
$$V_{\text{spin-dep.}} = \frac{1}{m_c^2} \left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r} \right) \vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3} T \right]$$

+ relativistic corrections!

[Godfrey & Isgur, PRD 32 (1985) 189]

[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]





- Before 2003:
 - Good agreement between theory and experiment, particularly beneath open charm thresholds

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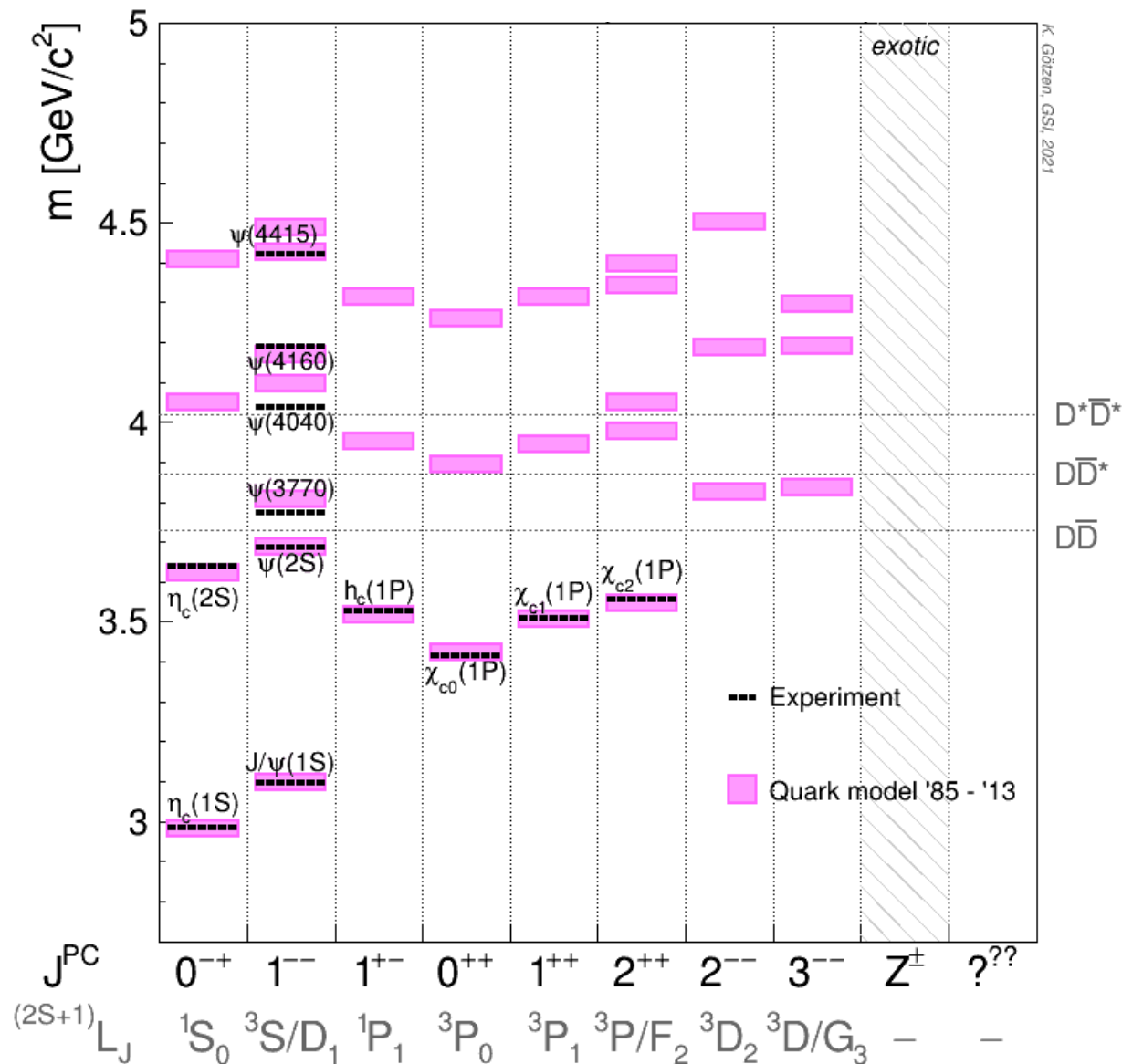
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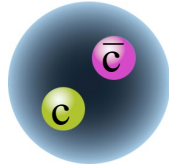
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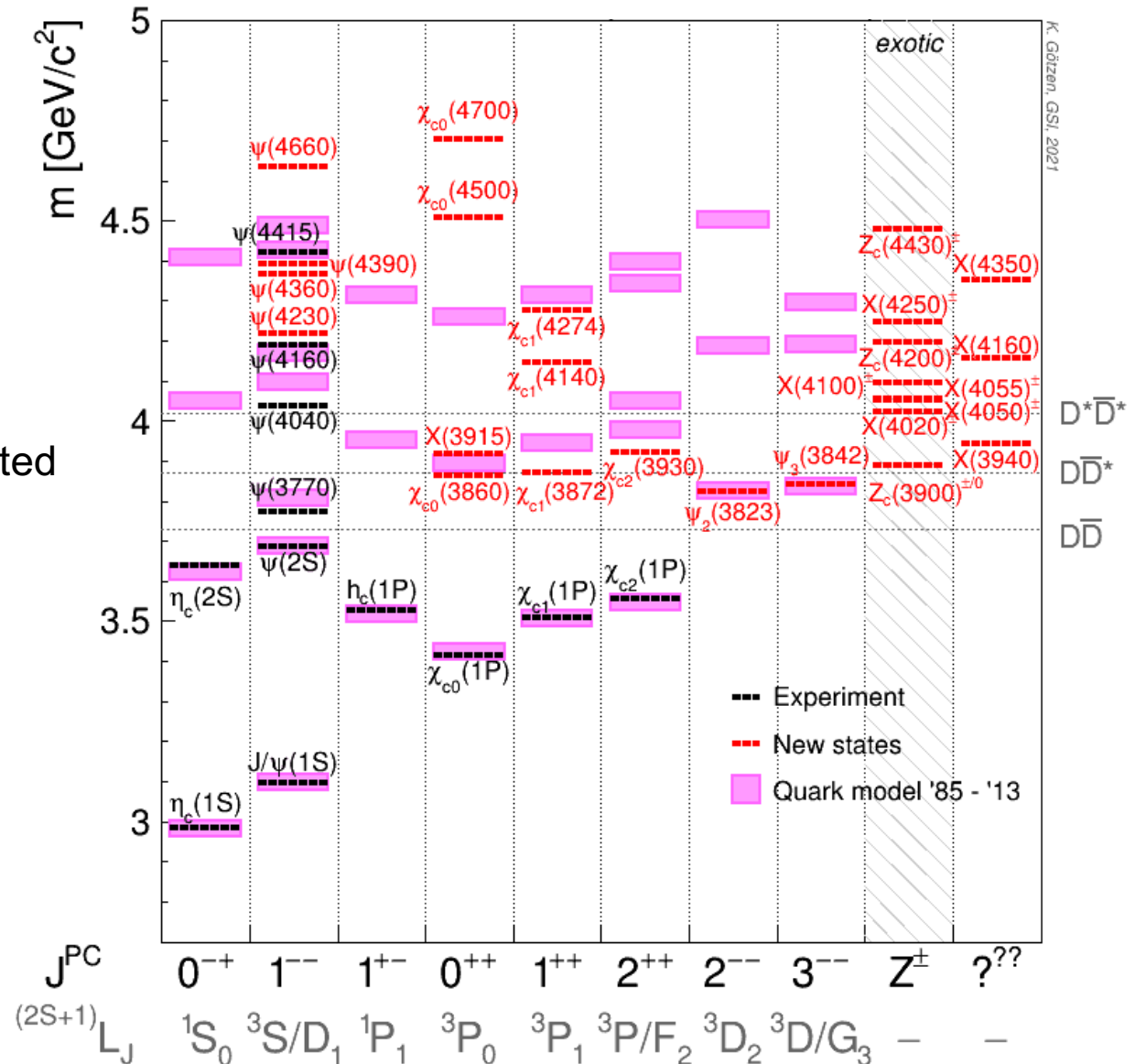
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+ relativistic corrections!

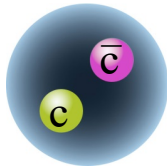
[Godfrey & Isgur, PRD 32 (1985) 189]

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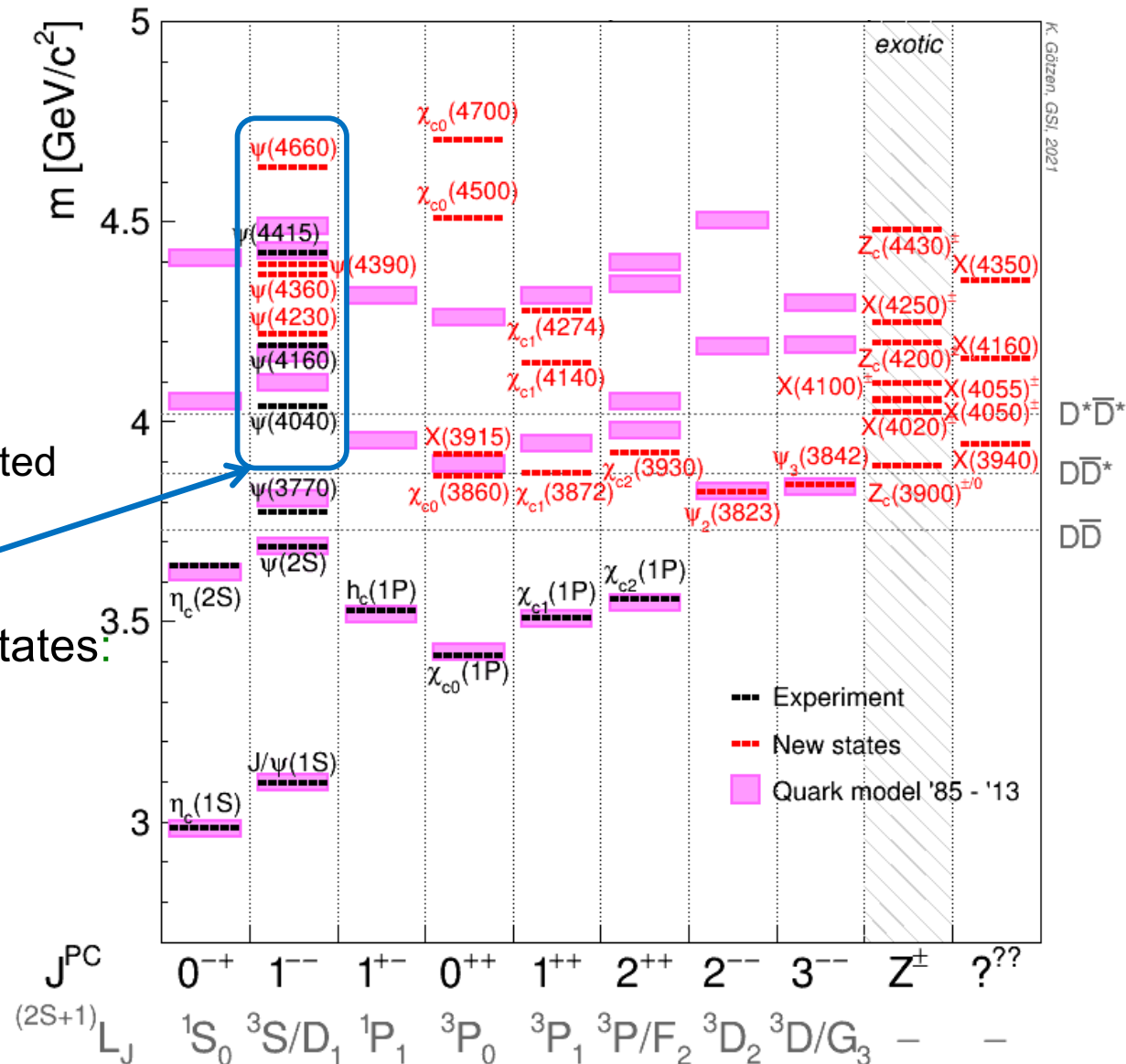


K. Götzen, GSI, 2021

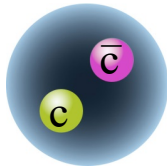
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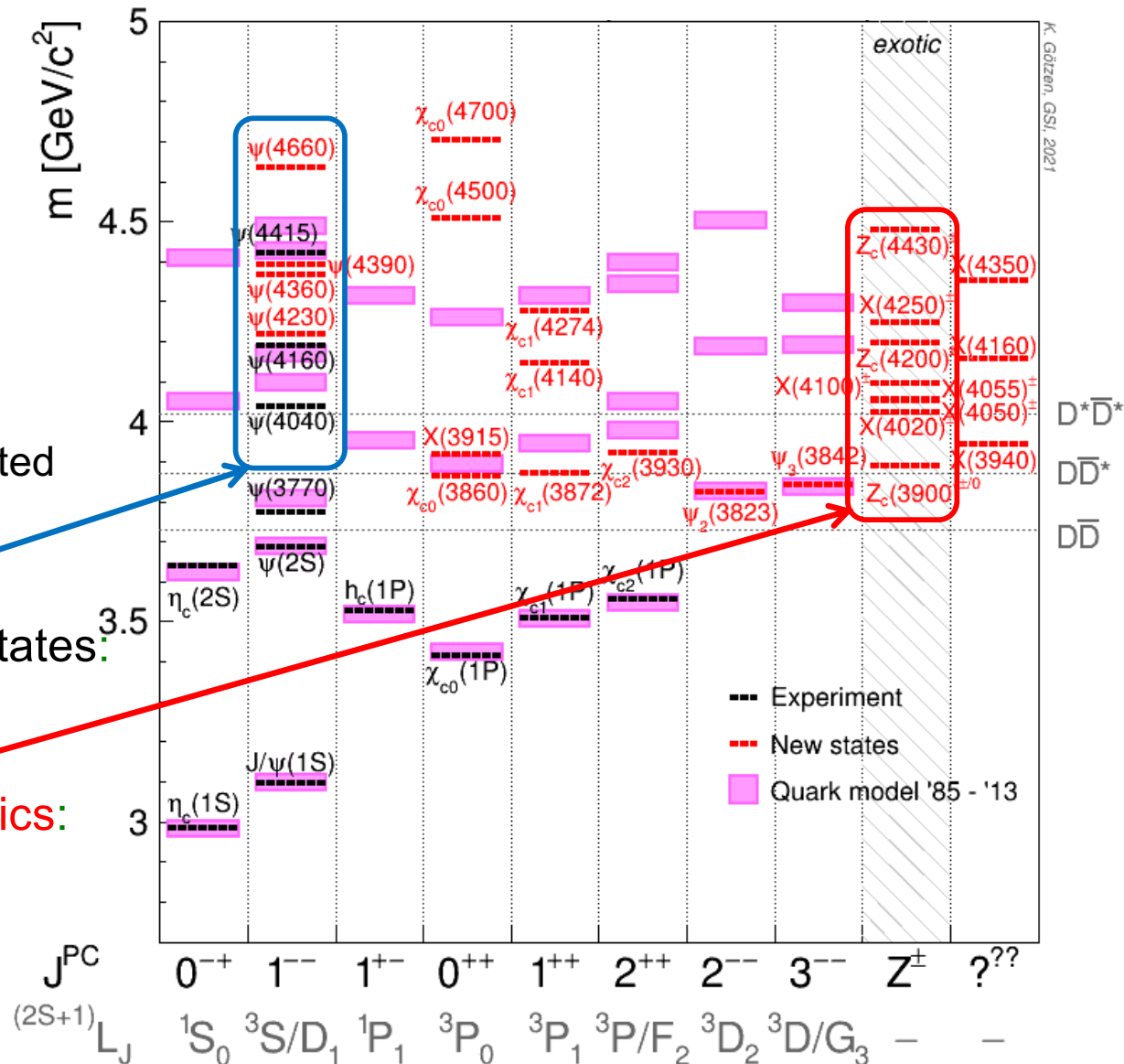
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 - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
 - Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: $Y(4260)$, ..., $Y(4660)$



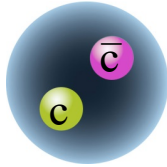
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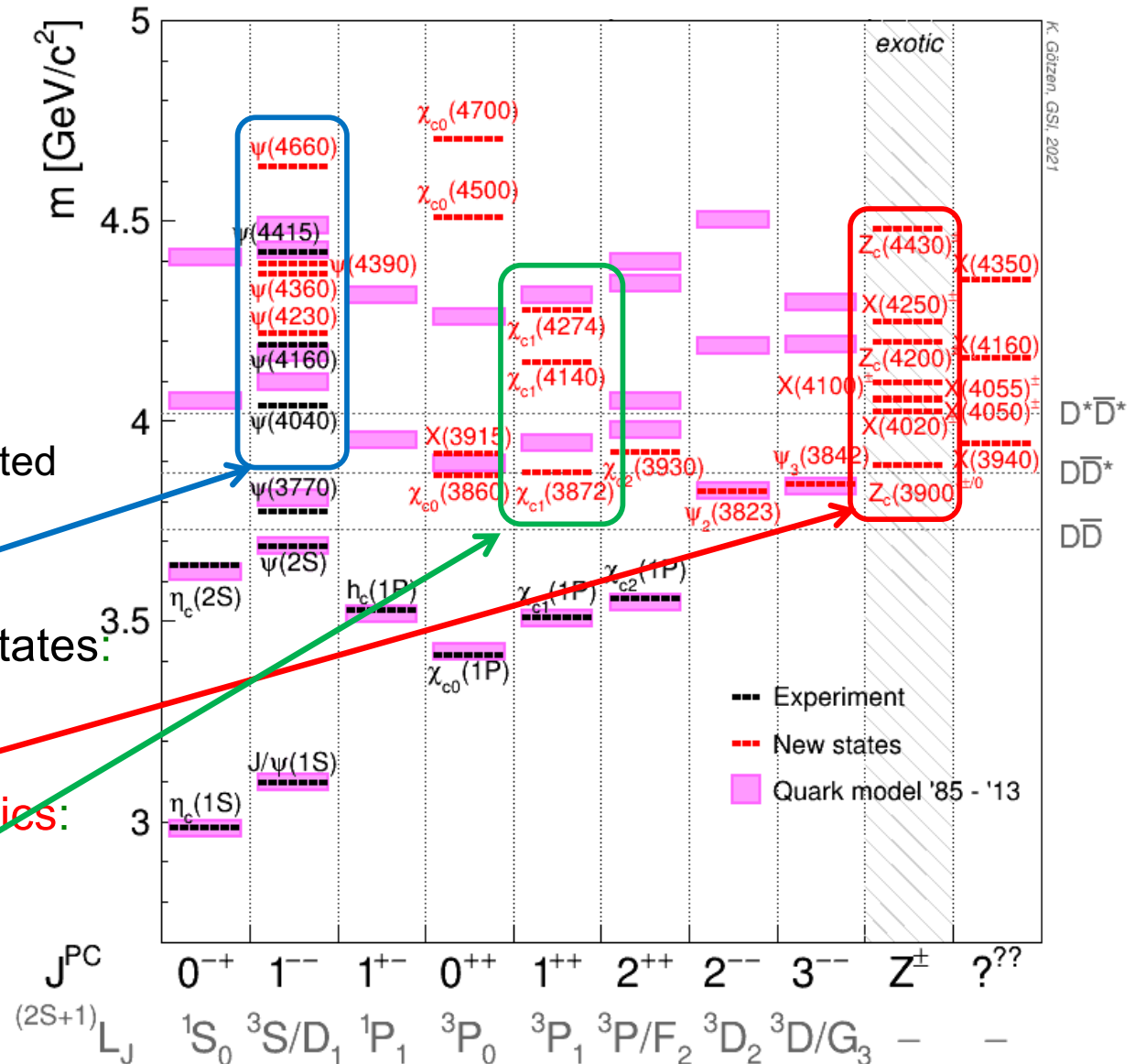
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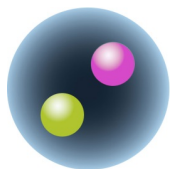


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- Several charged **manifestly exotics**: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$
- The X states – the $\chi_{c1}(3872)$ was the first observed in 2003



Simple Quark model

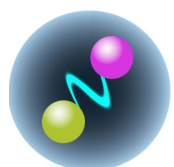
- Mesons: Color neutral $q\bar{q}$ systems



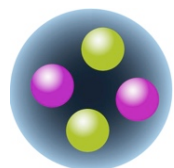
Conventional ($q\bar{q}$)

QCD

- Meson states beyond $q\bar{q}$



Hybrid ($q\bar{q}$)g

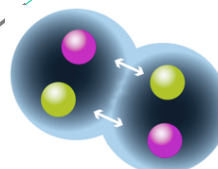


Tetraquark ($q\bar{q}q\bar{q}$)

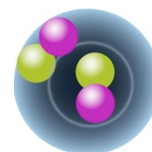


Glue-ball (gg) or (ggg)

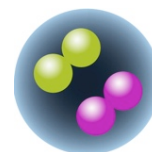
Alternative 4-quark configurations:



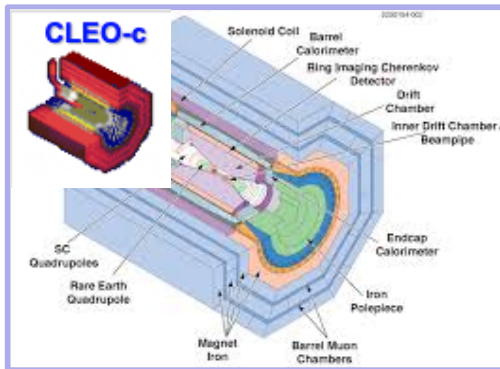
Molecule ($q\bar{q}$)($q\bar{q}$)



Hadro-quarkonium ($Q\bar{Q}$)($q\bar{q}$)



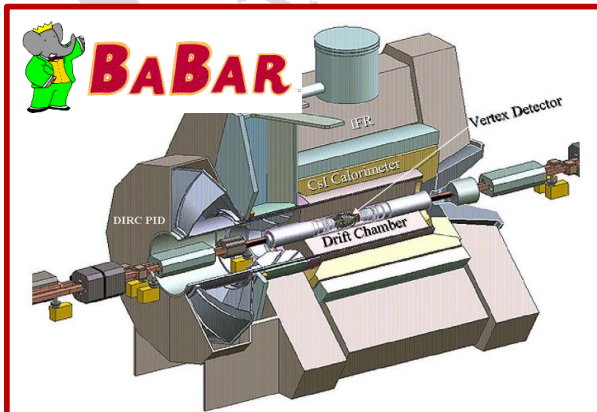
Di-quarkonium (qq)($\bar{q}q$)



- Data taking 1980 – 2000 (2002 – 2008)
 - $E_{\text{cms}} \leq 3 - 12 \text{ GeV}$
 - Luminosity: $\sim 24 \text{ fb}^{-1}$ (plus $\sim 10 \text{ fb}^{-1}$)

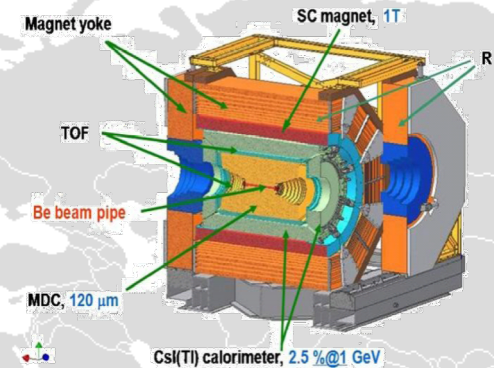
Cornell University (CESR)

SLAC Stanford (PEP-II)



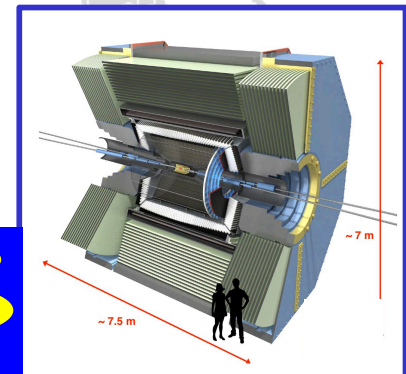
- Data taking 1999 – 2008
 - $E_{\text{cms}} \leq 10.58 \text{ GeV}$
 - Luminosity: 557.4 fb^{-1}

- Data taking since 2008
 - $E_{\text{cms}} \leq 4.6 \text{ GeV} (\leq 5 \text{ GeV})$
 - Luminosity $\sim 22 \text{ fb}^{-1}$ (XYZ)

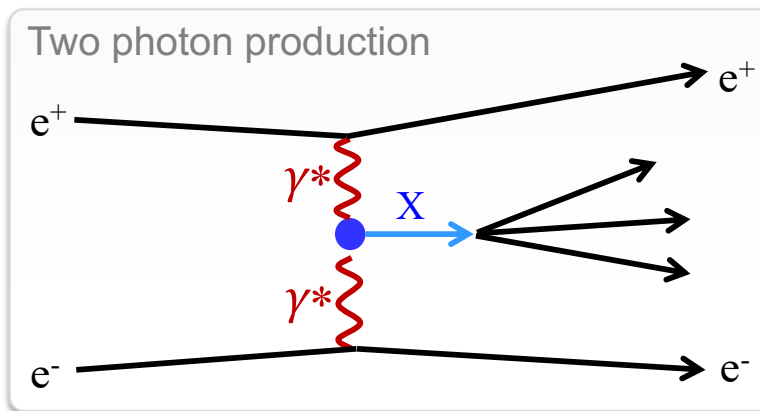
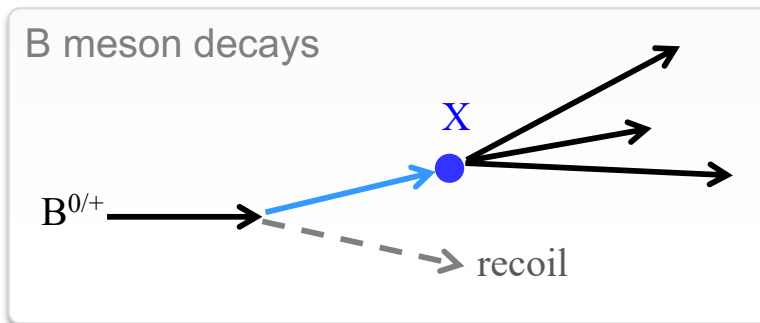
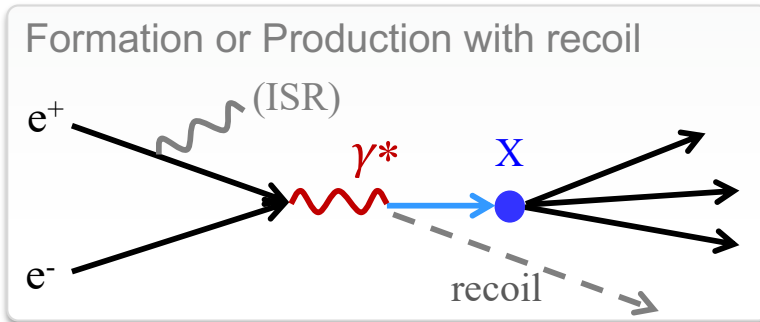


IHEP Beijing (BEPC-II)

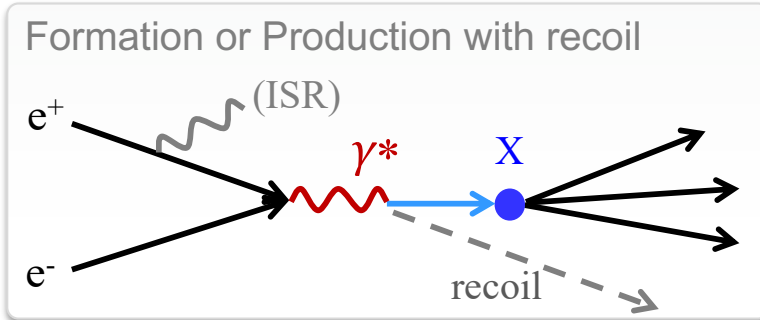
(Super) KEKB Tsukuba



- Data taking 1999 – 2010 (2019 – 2031+)
 - $E_{\text{cms}} \leq 10.58 \text{ GeV} (\leq 11 \text{ GeV})$
 - Luminosity: 980 fb^{-1} (50 ab^{-1} by 2031)



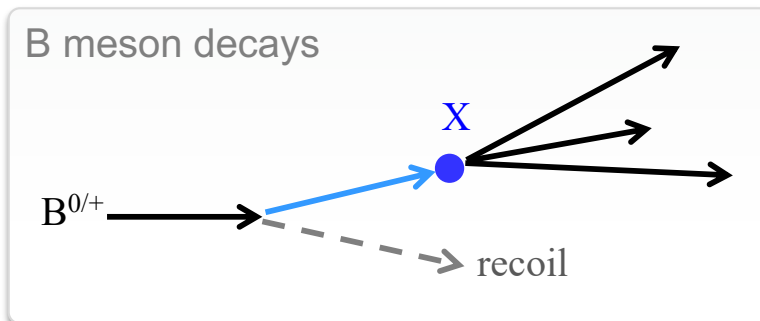
- Formation & Production with recoil particle(s)
 - CLEO(-c), BaBar, Belle(II) ($E_{\text{cms}} \leq 12 \text{ GeV}$)
 - BESIII ($E_{\text{cms}} \leq 4.9 \text{ GeV}$)
- Double charmonium production
 - CLEO, BaBar, Belle(II) ($E_{\text{cms}} \leq 12 \text{ GeV}$)
- B meson decays
 - CLEO, BaBar, Belle(II) ($E_{\text{cms}} \leq 12 \text{ GeV}$)
(also LHCb: pp (7 TeV/c))
- Two photon production
 - BaBar, CLEO(-c), Belle(II) ($E_{\text{cms}} \leq 12 \text{ GeV}$)
 - BESIII ($E_{\text{cms}} \leq 4.9 \text{ GeV}$)



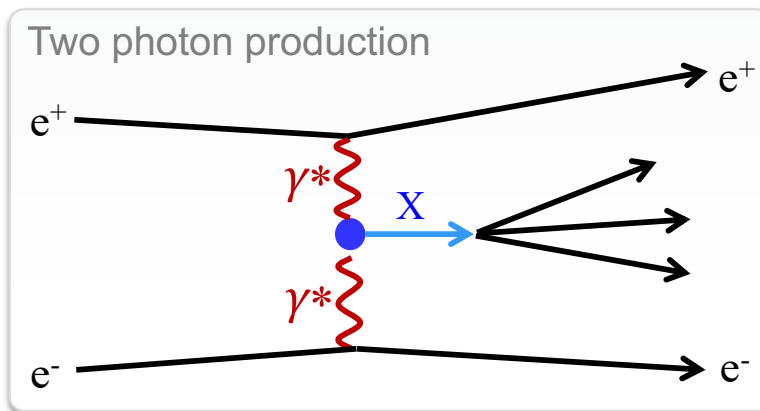
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→ *not covered in this talk*



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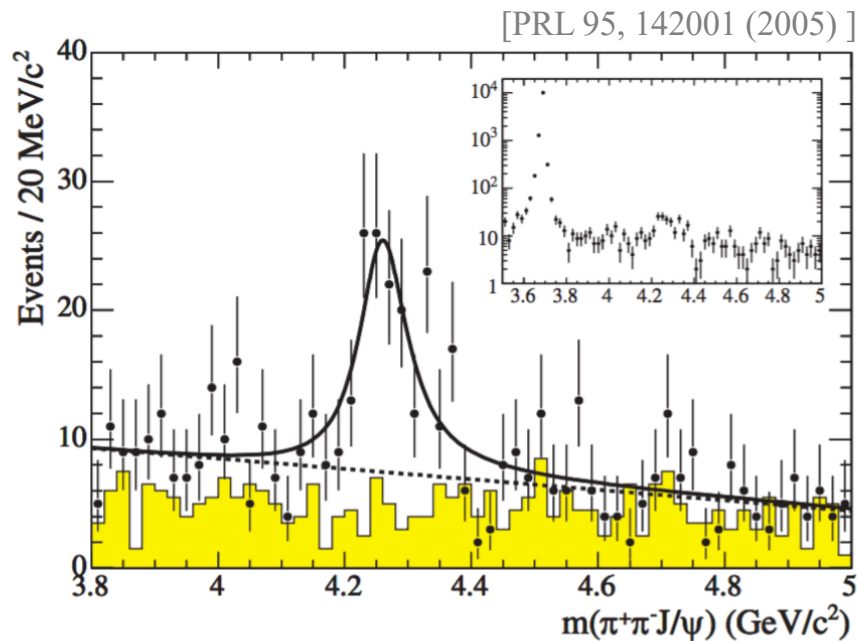
→ *not covered in this talk*

The $Y(4260)$ and further supernumerary vector states

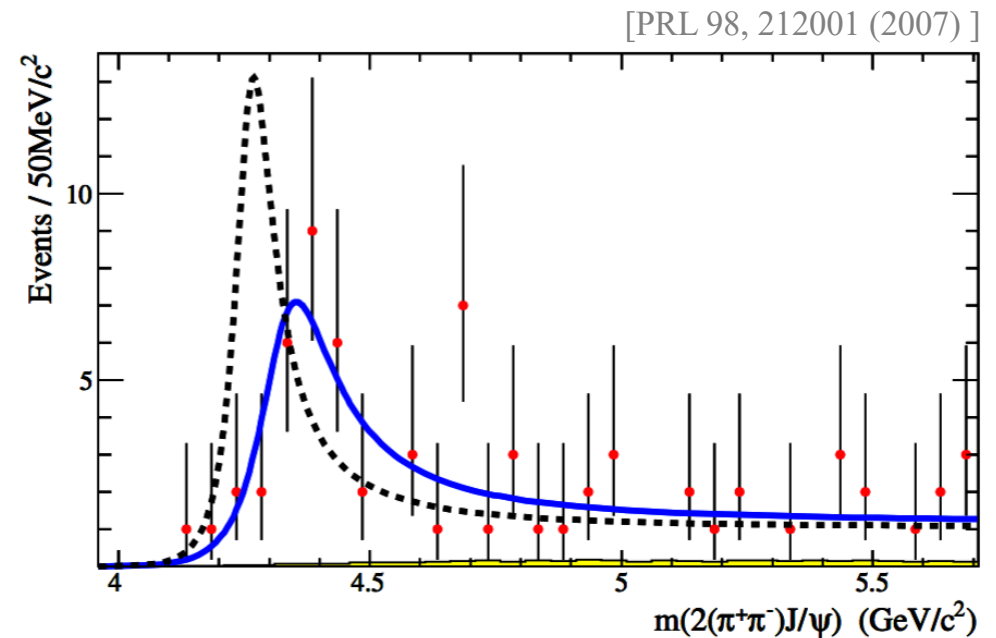
The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

Some history:

$$e^+e^- \rightarrow J/\psi\pi^+\pi^-$$



$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$



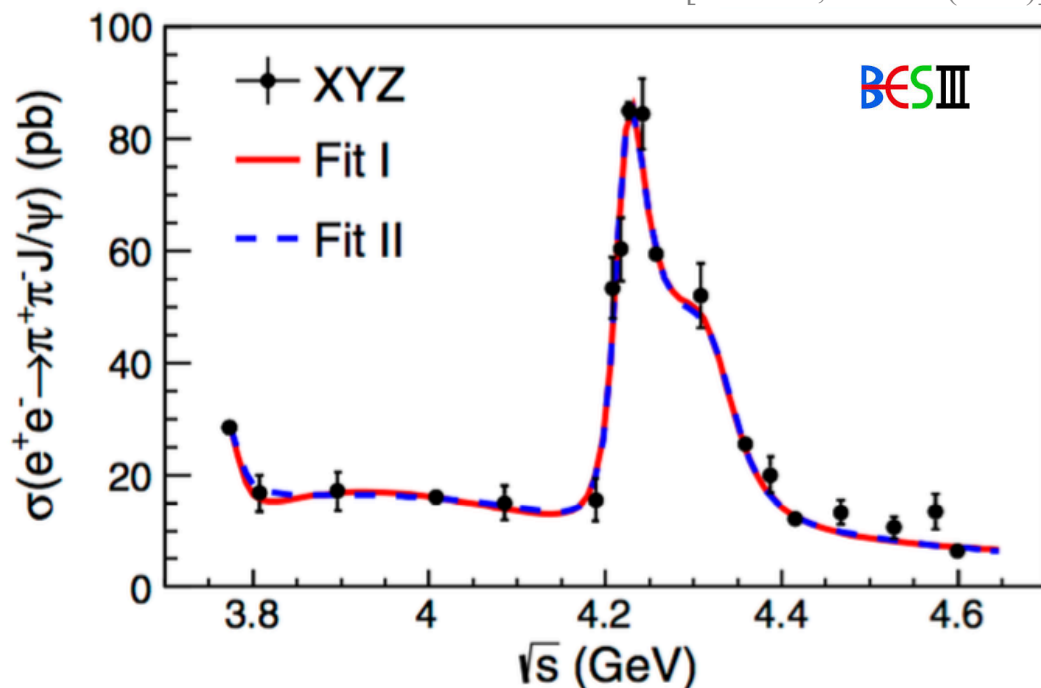
- Discovery of the Y(4260) using ISR by BaBar in $J/\psi\pi^+\pi^-$

- Discovery of the Y(4360) using ISR by BaBar in $\psi(2S)\pi^+\pi^-$

BESIII result, published

$$e^+e^- \rightarrow J/\psi\pi^+\pi^-$$

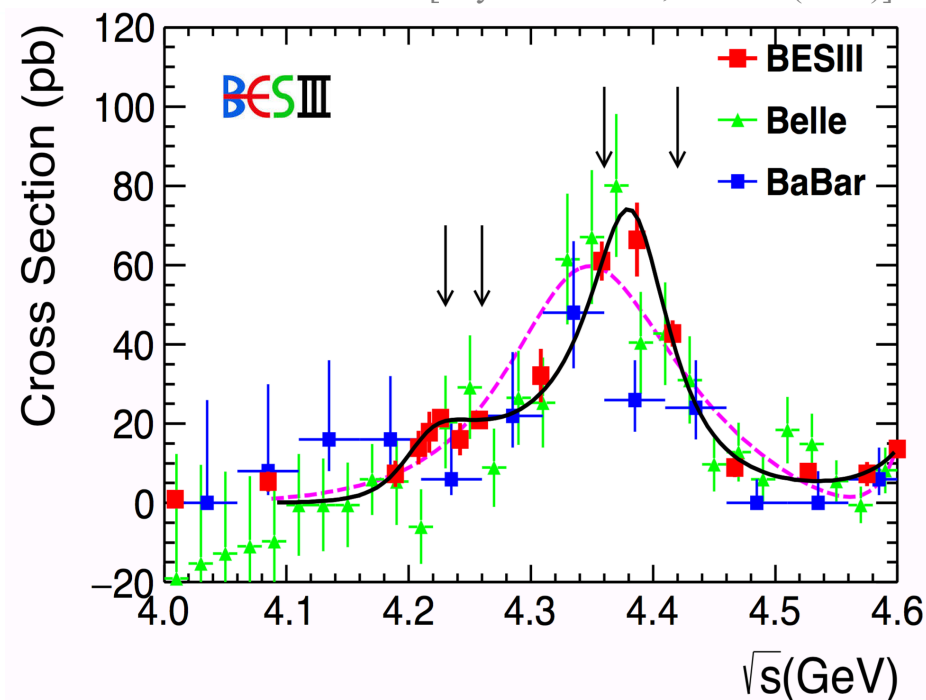
[PRL 118, 092001 (2017)]



- Cross-section inconsistent with the single resonance $Y(4260)$!
- Two favoured over one by $>7\sigma$

$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

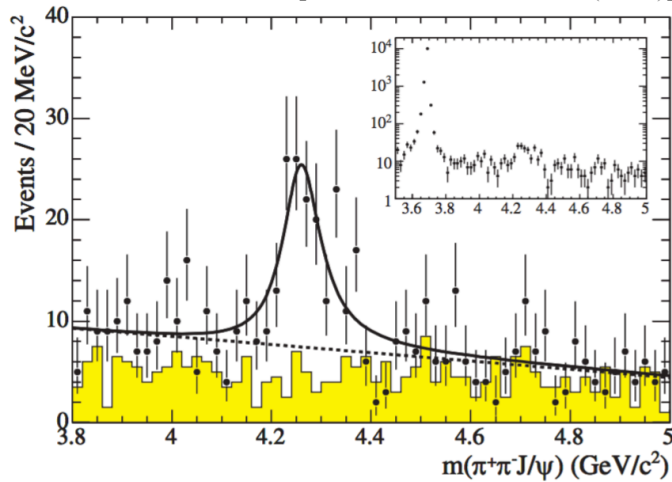
[Phys. Rev. D 96, 032004 (2017)]



- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: $Y(4220)$ and $Y(4390)$

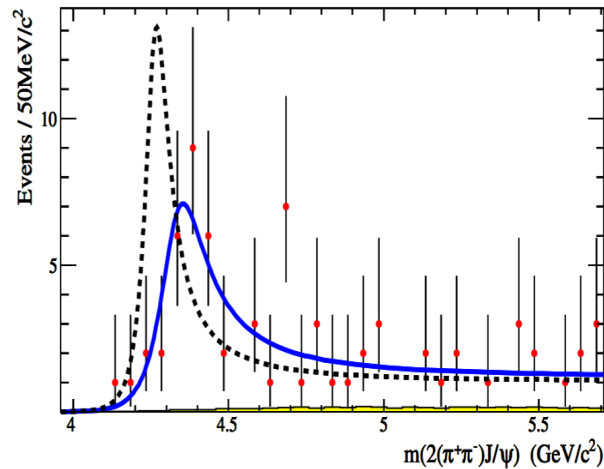
$$e^+e^- \rightarrow J/\psi\pi^+\pi^-$$

[BaBar, PRL 95, 142001 (2005)]

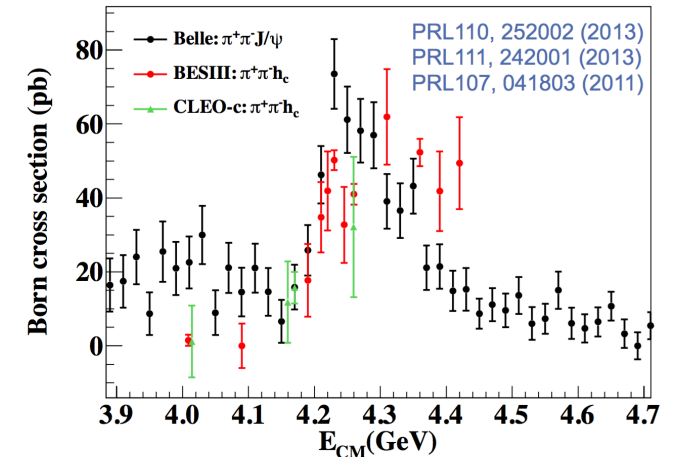


$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

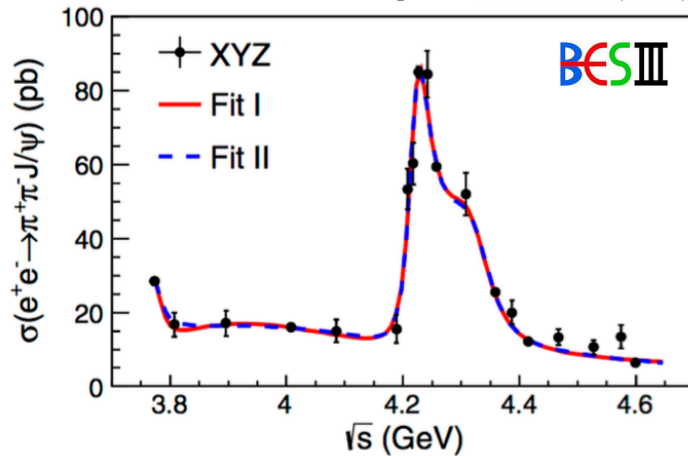
[BaBar, PRL 98, 212001 (2007)]



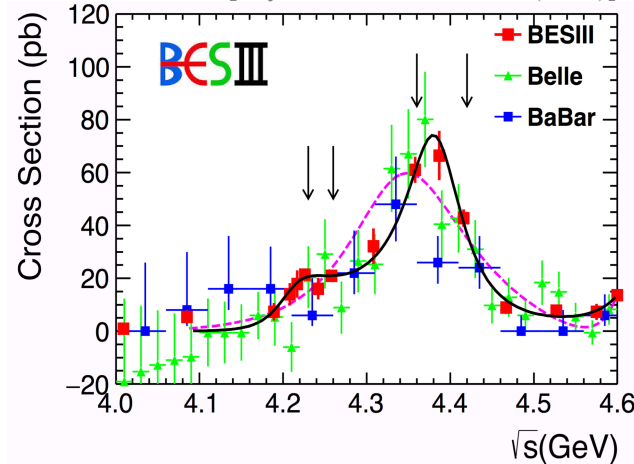
$$e^+e^- \rightarrow h_c\pi^+\pi^-$$



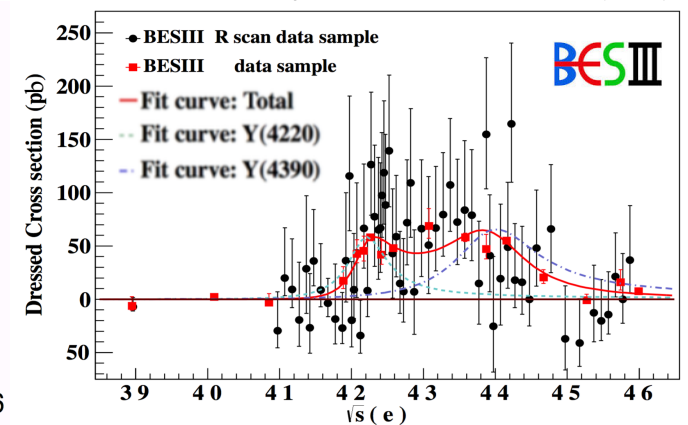
[PRL 118, 092001 (2017)]



[Phys. Rev. D 96, 032004 (2017)]

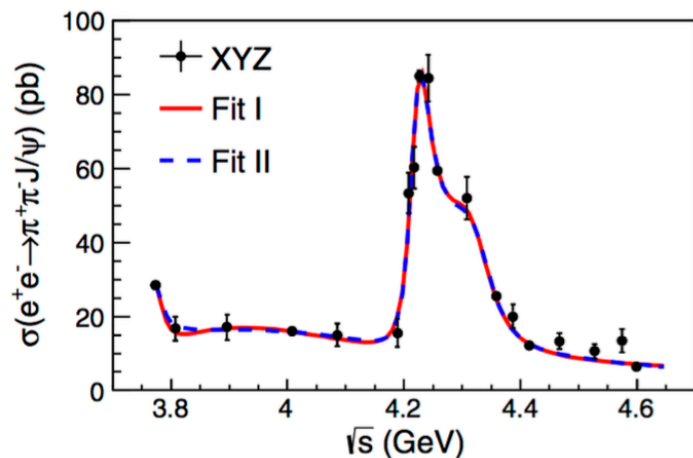


[Phys. Rev. Lett. 118 092002 (2017)]

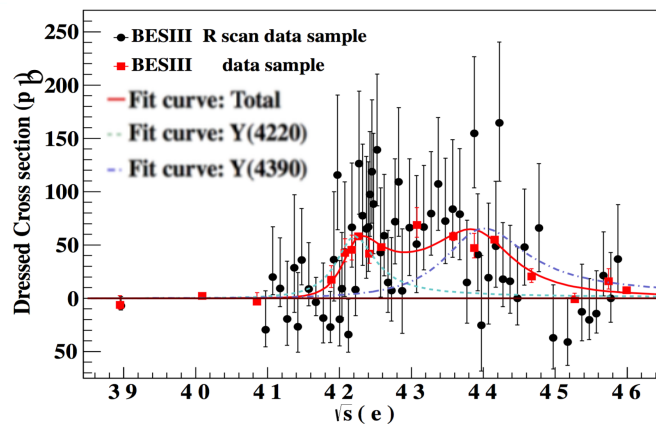


Two structures now resolved: $Y(4260) \rightarrow Y(4220)$, $Y(4360) \rightarrow Y(4390)$

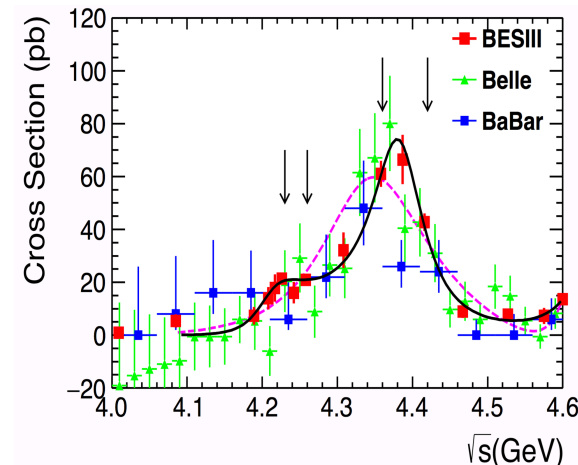
$$e^+e^- \rightarrow J/\psi \pi^+ \pi^-$$



$$e^+e^- \rightarrow \psi(2S) \pi^+ \pi^-$$

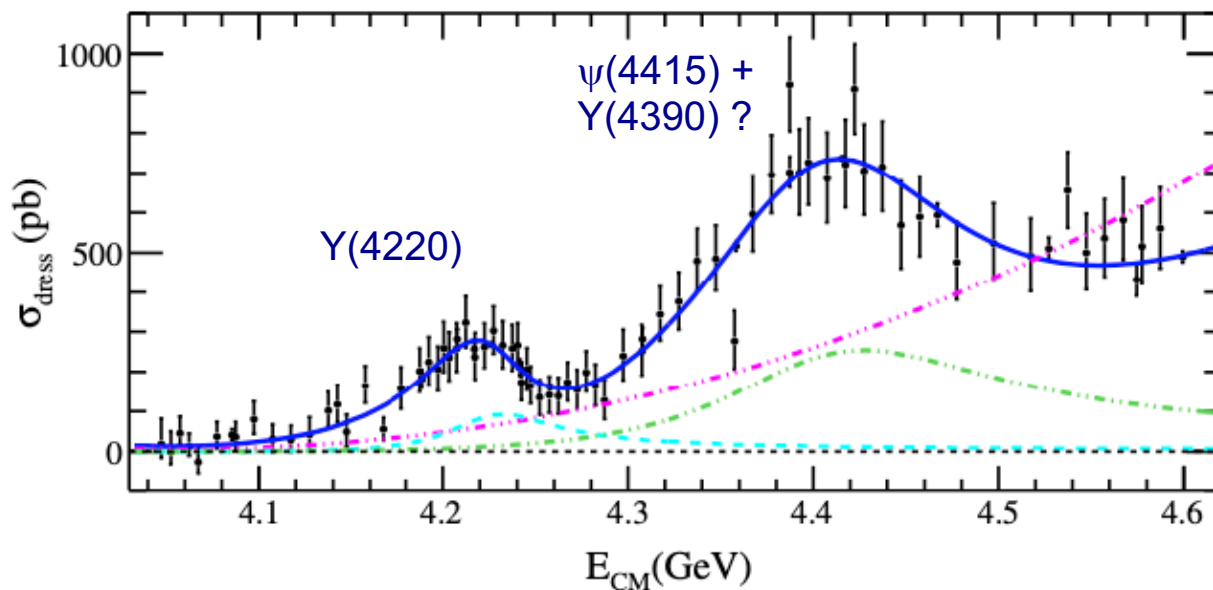


$$e^+e^- \rightarrow h_c \pi^+ \pi^-$$



$$e^+e^- \rightarrow D^0 D^{*-} \pi^+$$

[PRL 122, 102002 (2019)]



Y(4220):

- $M = (4228.6 \pm 4.1 \pm 6.3) \text{ MeV}/c^2$
- $\Gamma = (77.0 \pm 6.8 \pm 6.3) \text{ MeV}/c^2$

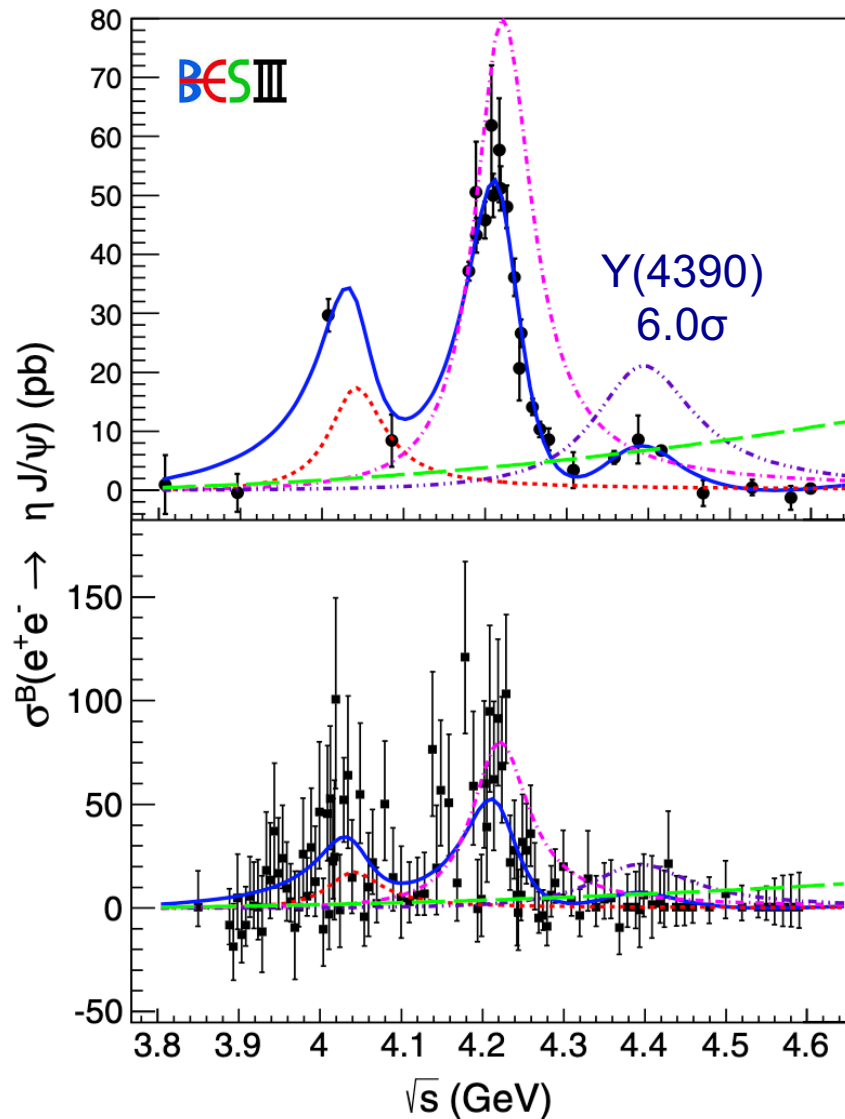
Y state at about 4.40 GeV:

- strongly model dependent

- => First Y decays to open-charm
- => Consistency with structures in $J/\psi / h_c / \psi(2S) \pi\pi$

$$e^+e^- \rightarrow J/\psi \eta$$

[Phys. Rev. D 102, 031101 (2020)]

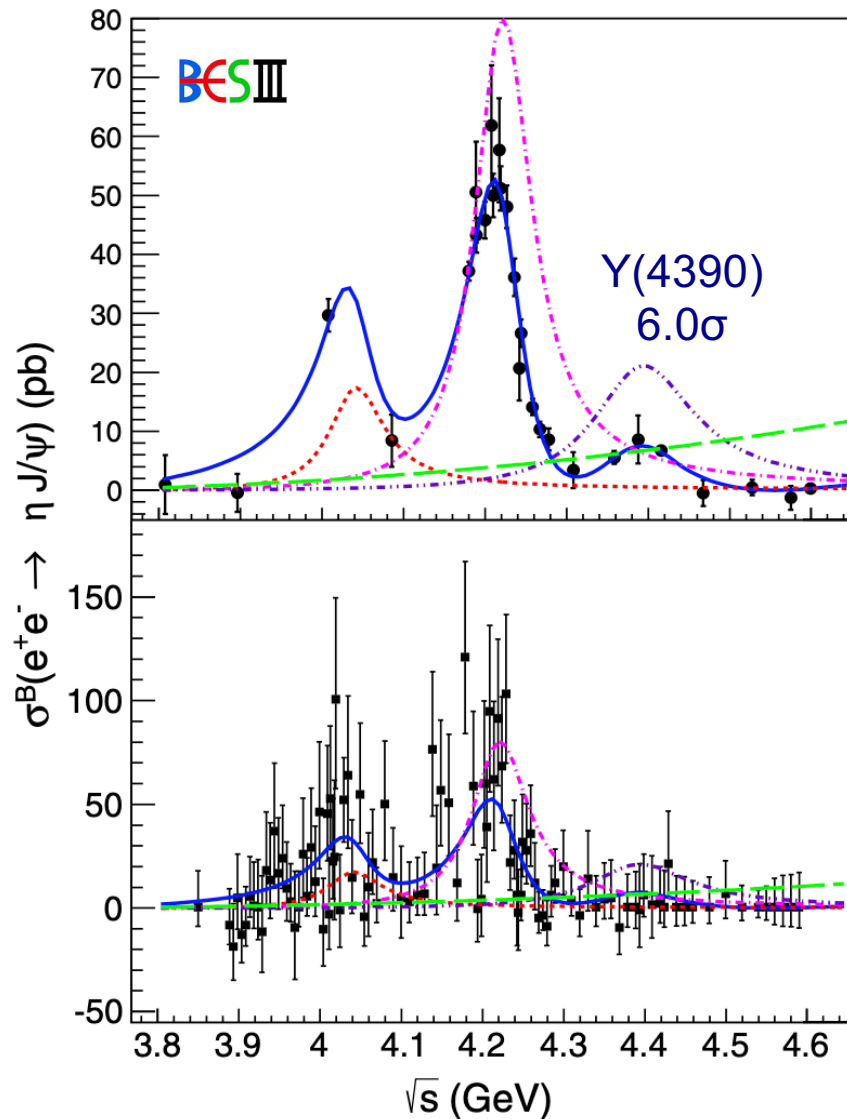


- Simultaneous maximum-likelihood fit
(Top: High stat. XYZ data, Bottom: Scan data)
- $\psi(4040)$ assumed, $Y(4220)$, $Y(4390)$?
- Significance of $Y(4390) = 6.0 \sigma$

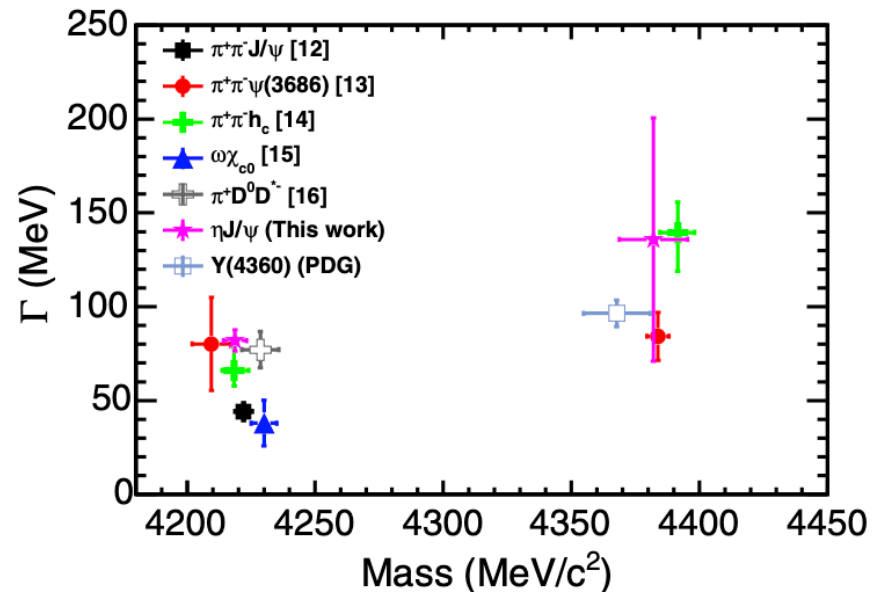
Parameters	Solution 1	Solution 2	Solution 3
M_1 (MeV/ c^2)		4039(fixed)	
Γ_1 (MeV)		80(fixed)	
$\Gamma_1^{e^+e^-} Br_1$ (eV)	1.5 ± 0.3	1.4 ± 0.3	7.0 ± 0.6
ϕ_1 (rad)	3.3 ± 0.3	3.1 ± 0.3	4.5 ± 0.2
M_2 (MeV/ c^2)		4218.6 ± 3.8	
Γ_2 (MeV)		82.0 ± 5.7	
$\Gamma_2^{e^+e^-} Br_2$ (eV)	8.0 ± 1.7	4.8 ± 1.0	7.0 ± 1.5
ϕ_2 (rad)	4.2 ± 0.4	3.6 ± 0.3	2.9 ± 0.3
M_3 (MeV/ c^2)		4382.0 ± 13.3	
Γ_3 (MeV)		135.8 ± 60.8	
$\Gamma_3^{e^+e^-} Br_3$ (eV)	3.4 ± 2.2	1.5 ± 1.0	1.7 ± 1.1
ϕ_3 (rad)	2.8 ± 0.4	3.3 ± 0.4	3.0 ± 0.4

$$e^+e^- \rightarrow J/\psi \eta$$

[Phys. Rev. D 102, 031101 (2020)]

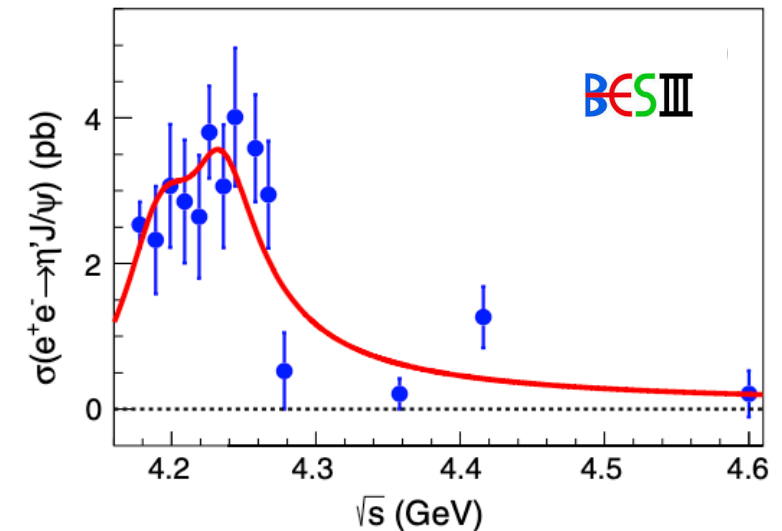
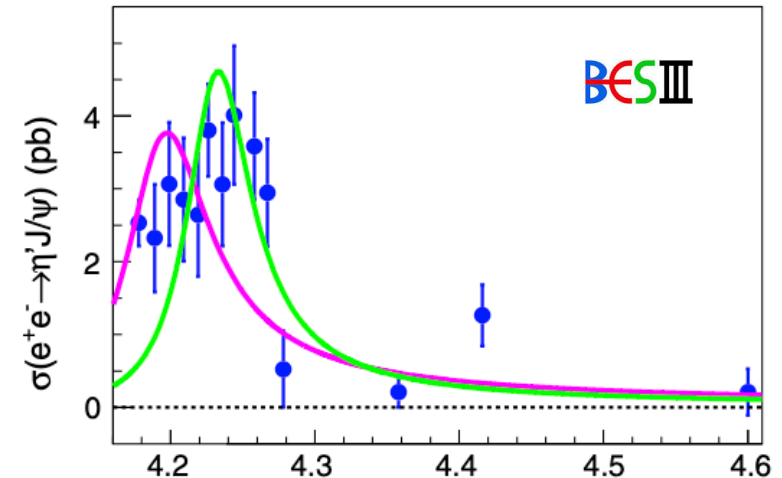
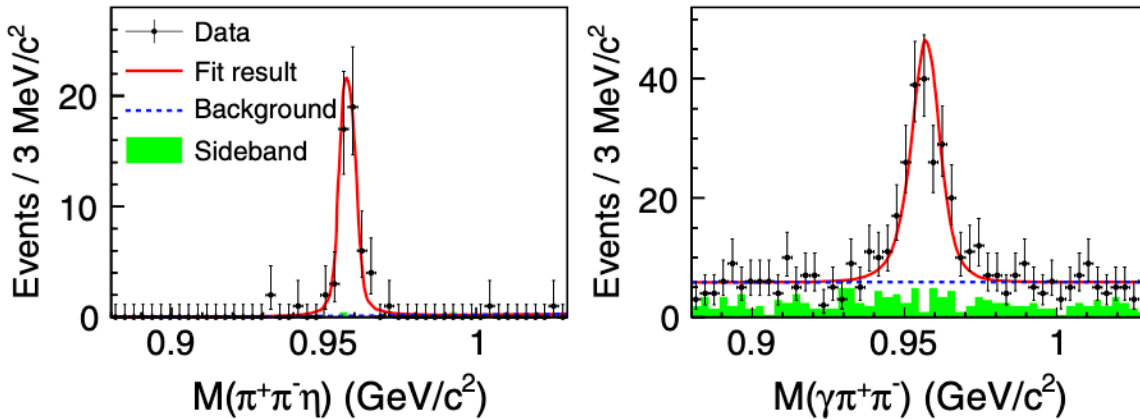


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(Top: High stat. XYZ data, Bottom: Scan data)
- $\psi(4040)$ assumed, $Y(4220)$, $Y(4390)$?
- Significance of $Y(4390) = 6.0 \sigma$
- $Y(4220)$ & $Y(4390)$ mass and width compilation vs. $Y(4360)$ from PDG:



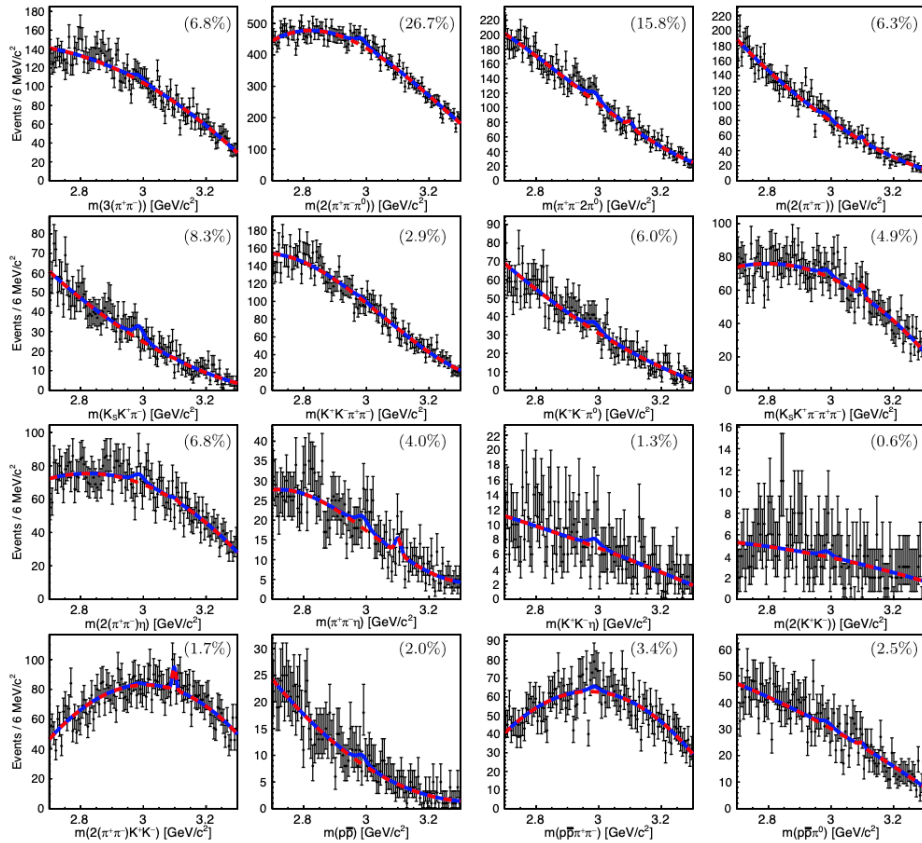
$$e^+e^- \rightarrow J/\psi \eta'$$

[Phys. Rev. D 101, 012008 (2020)]

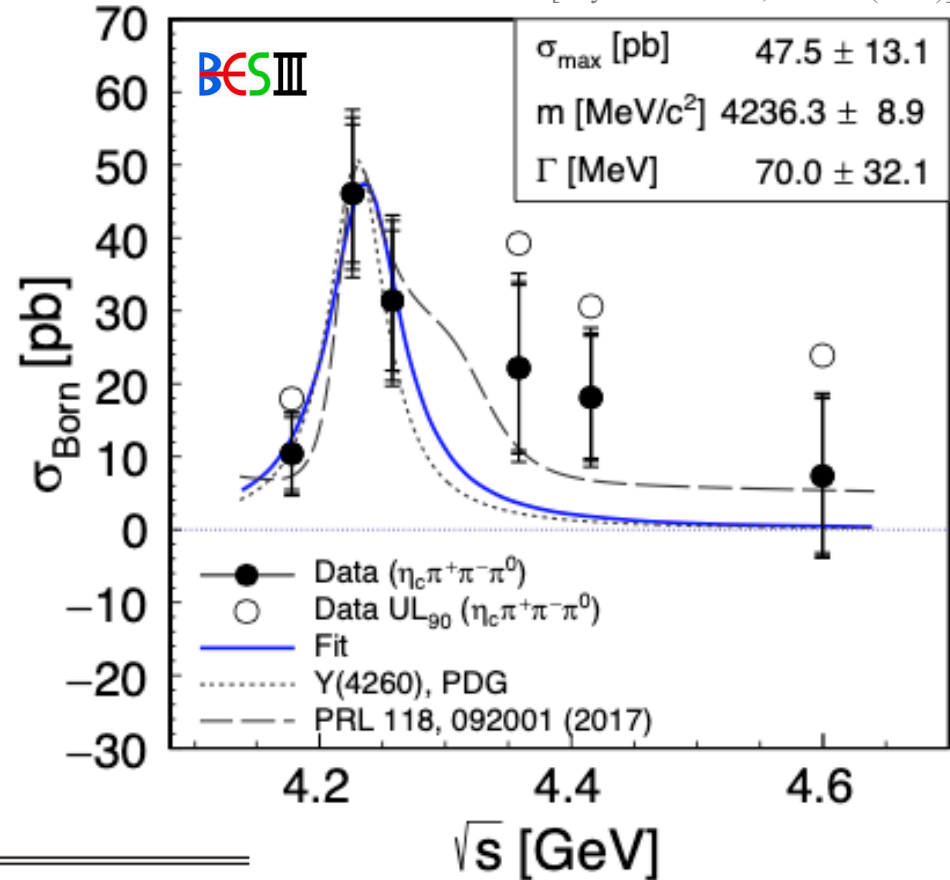


- Simultaneous maximum-likelihood fit
(to the two η' decay modes)
- Fit to cross section σ [(m, Γ) fixed to PDG]
 - Single $\psi(4160)$ or $\Upsilon(4260)$
 - Coherent sum of $\psi(4160)$ and $\Upsilon(4260)$
- Coherent sum preferred by data
 - 4.0σ and 6.3σ , respectively
 - Xsec σ an order of magnitude smaller than the one for $J/\psi \eta$
- Higher statistics needed ...

$$e^+e^- \rightarrow \eta_c \pi^+ \pi^- \pi^0$$



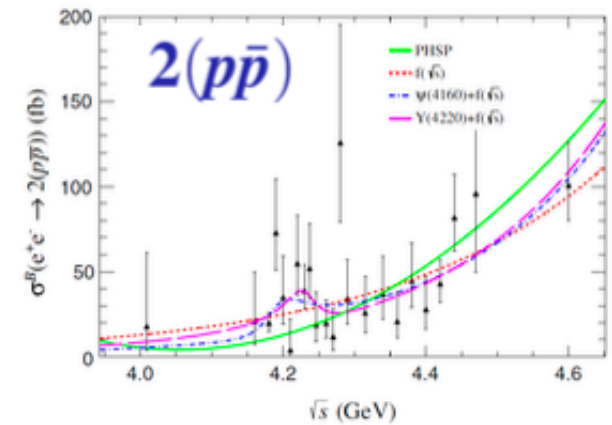
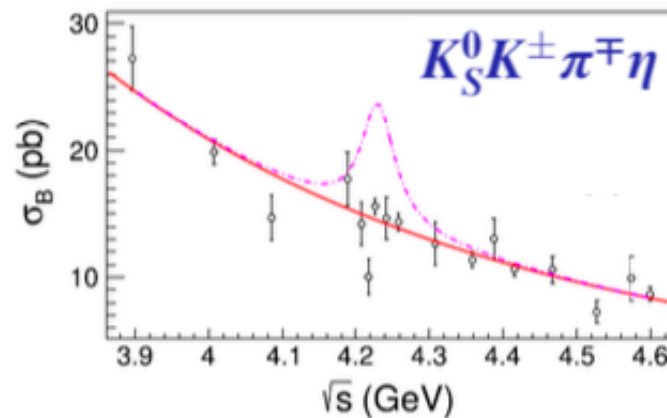
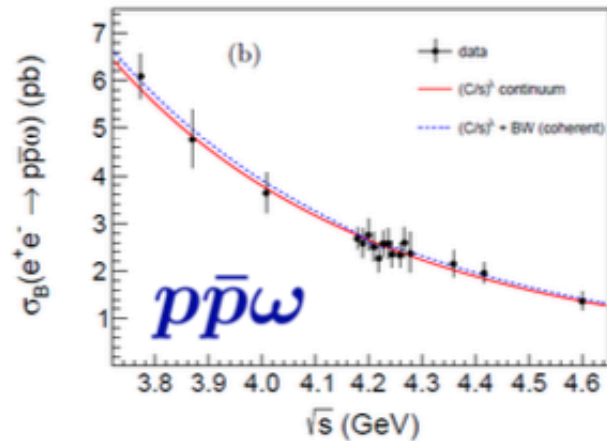
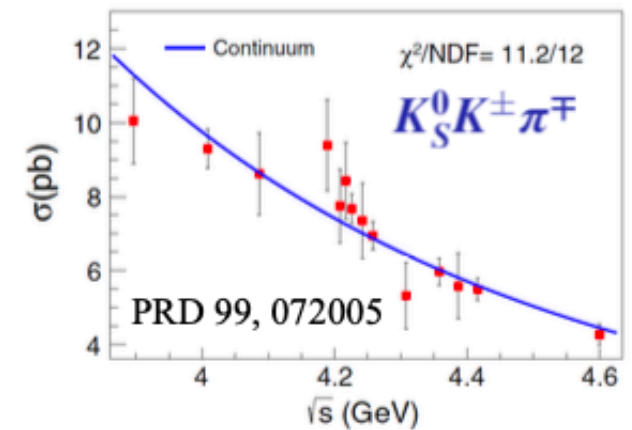
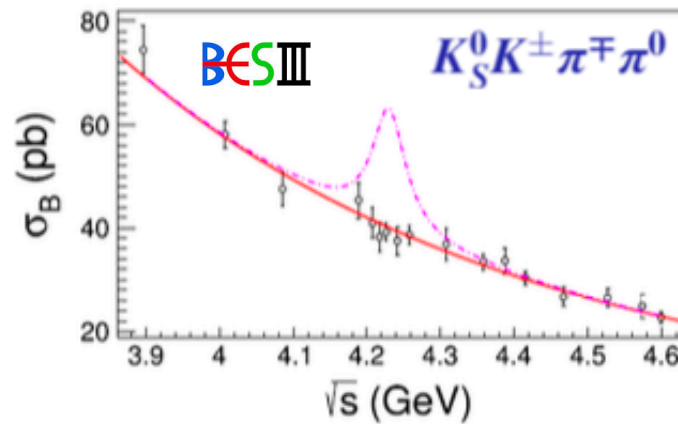
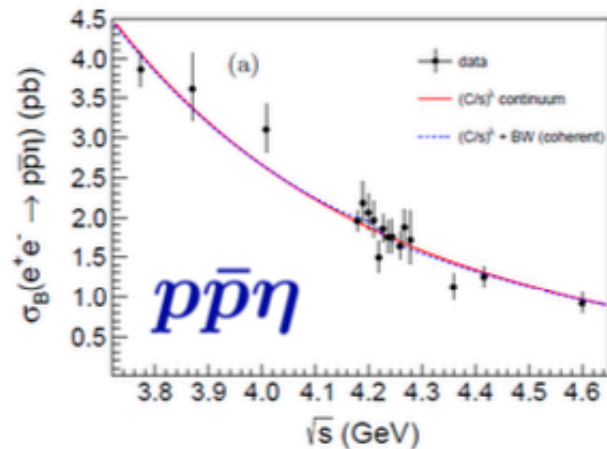
[Phys. Rev. D 103, 032006 (2021)]



$$e^+e^- \rightarrow \eta_c \pi^+ \pi^- \pi^0$$

\sqrt{s} [GeV]	\mathcal{L} [pb^{-1}]	N_{obs}	κ	f_{VP}	$\sum \epsilon_i \mathcal{B}_i$ [%]	σ_{Born} [pb]	UL ₉₀ [pb]	$S_{\text{stat}}/S_{\text{tot}}$ [σ]
4.1780	3189.0	530 ± 246	[0.720, 0.734]	1.056	2.0	10.4 ^{+5.0} _{-4.9} ± 2.9	17.9	2.2/1.9
4.2263	1091.7	786 ± 159	[0.716, 0.731]	1.056	2.0	46.1 ^{+9.5} _{-9.4} ± 6.6	61.0	5.1/4.6
4.2580	825.7	465 ± 134	[0.786, 0.824]	1.054	2.0	31.4 ^{+9.6} _{-9.6} ± 6.7	46.6	3.5/3.2
4.3583	539.8	242 ± 115	[0.802, 0.880]	1.051	2.1	22.2 ^{+11.4} _{-11.3} ± 6.2	39.2	2.2/1.9
4.4156	1073.6	379 ± 165	[0.780, 0.850]	1.053	2.2	18.1 ^{+8.4} _{-8.4} ± 4.5	30.6	2.3/2.1
4.5995	566.9	79 ± 102	[0.763, 0.807]	1.055	2.0	7.4 ^{+10.6} _{-10.5} ± 3.9	23.9	0.8/0.7

=> Clear evidence for
 $Y(4220) \rightarrow \eta_c \pi^+ \pi^- \pi^0$



arXiv:2102.04268

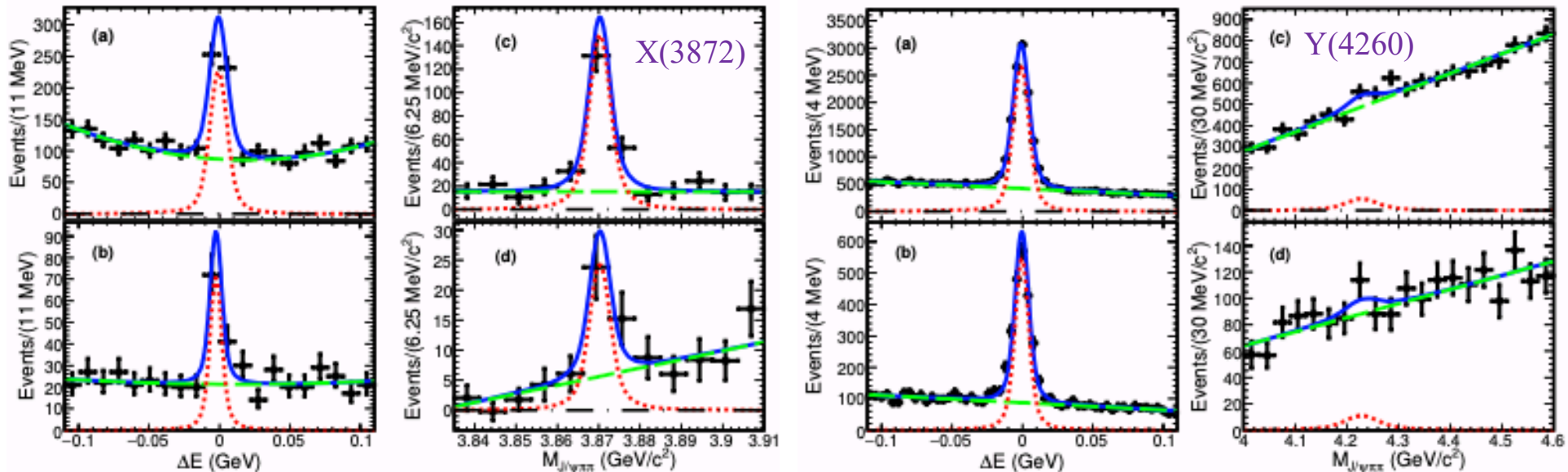
arXiv:1810.09395

PRD 103, 052003

- More and more possible decay channels to light hadrons investigated
- Still no clear evidence ...

$$B^+ \rightarrow Y(4260)K^+ \rightarrow J/\psi\pi^+\pi^-K^+$$

[Phys. Rev. D 99, 071102 (2019)]



$$B^0 \rightarrow Y(4260)K_S^0 \rightarrow J/\psi\pi^+\pi^-K_S^0$$

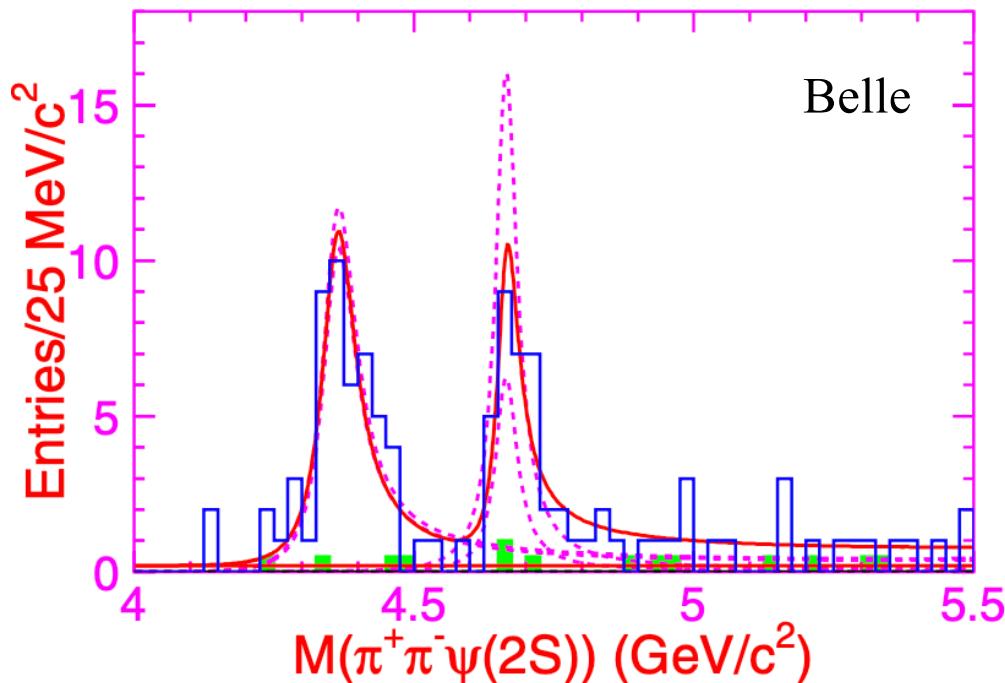
- Search for the Y(4260) in B^{+0} decays
- BaBar reported 3.1σ for B^+ [PRD 73, 011101 (2006)]
- No significant evidence ($2.1\sigma/0.9\sigma$), for B^0 first result
- Upper limits (CL90) on branching fractions
 - $\mathcal{B}(B^+ \rightarrow Y(4260)(\rightarrow J/\psi\pi^+\pi^-)K^+) < 1.4 \times 10^{-5}$
 - $\mathcal{B}(B^0 \rightarrow Y(4260)(\rightarrow J/\psi\pi^+\pi^-)K_S^0) < 1.7 \times 10^{-5}$



The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

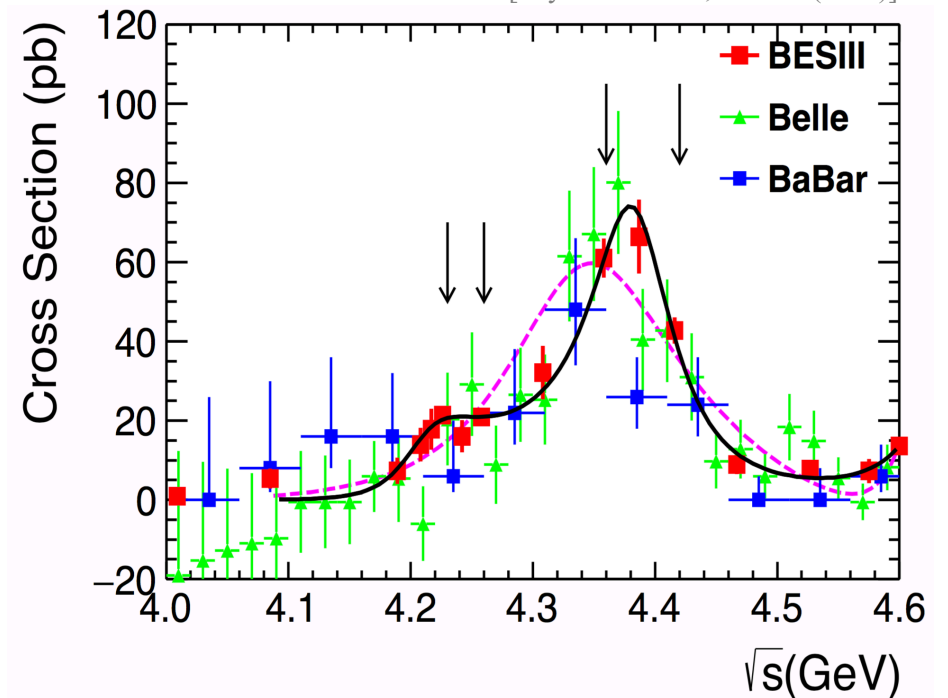
$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

[PRL 99, 142002 (2007)]



$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

[Phys. Rev. D 96, 032004 (2017)]



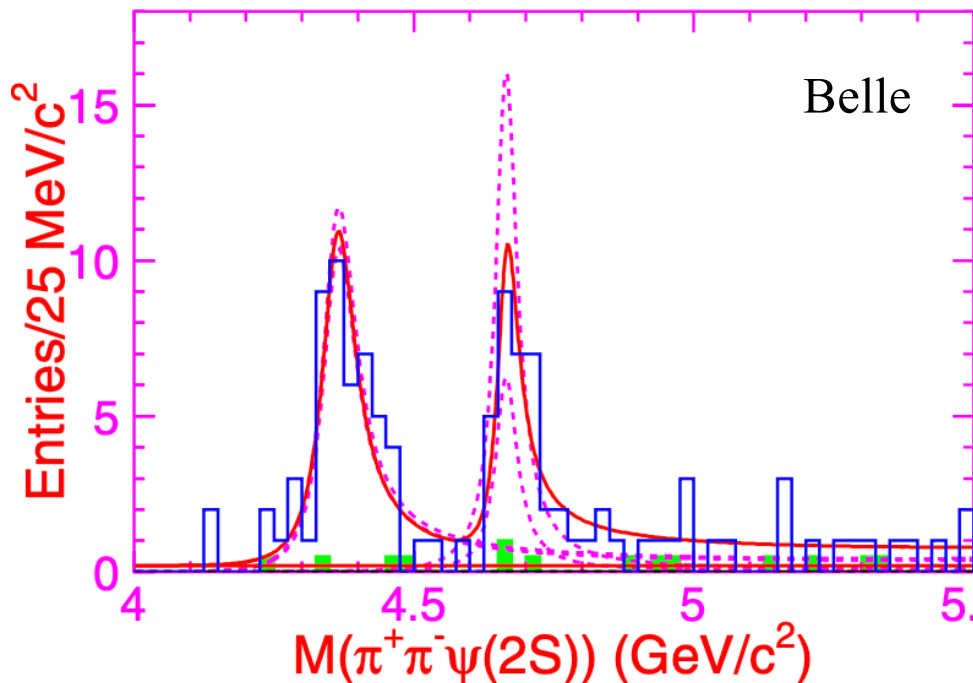
- Confirmation of the $Y(4360)$ in $\psi(2S)\pi^-\pi^+$ with a significance of 8σ
- First observation of $Y(4660)$ with 5.8σ

- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: $Y(4220)$ and $Y(4390)$

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

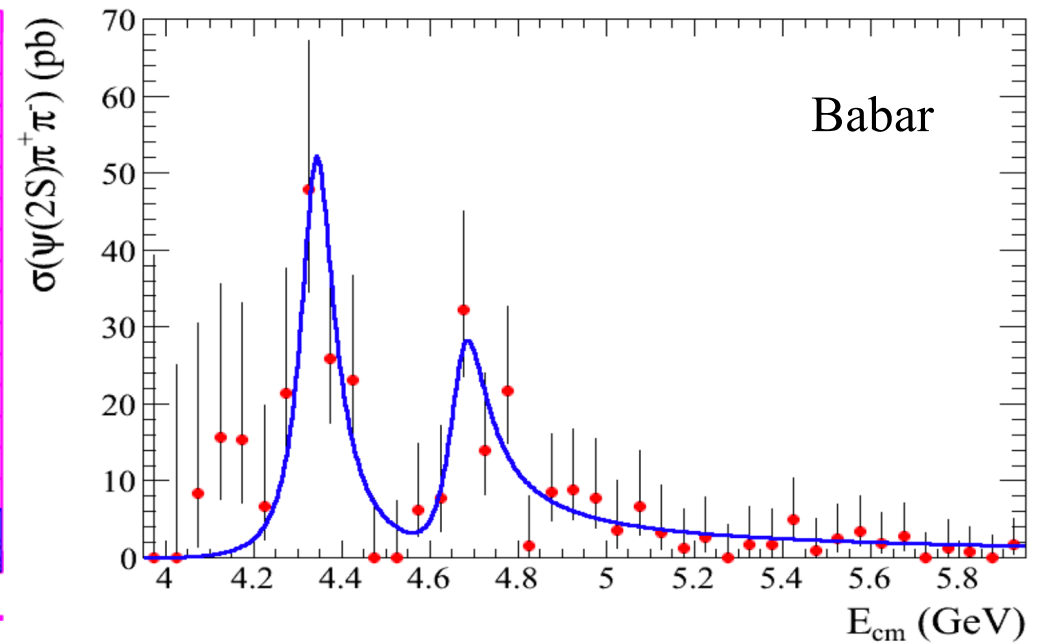
$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

[PRL 99, 142002 (2007)]



$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

[Phys. Rev. D 98, 111103 (2012)]



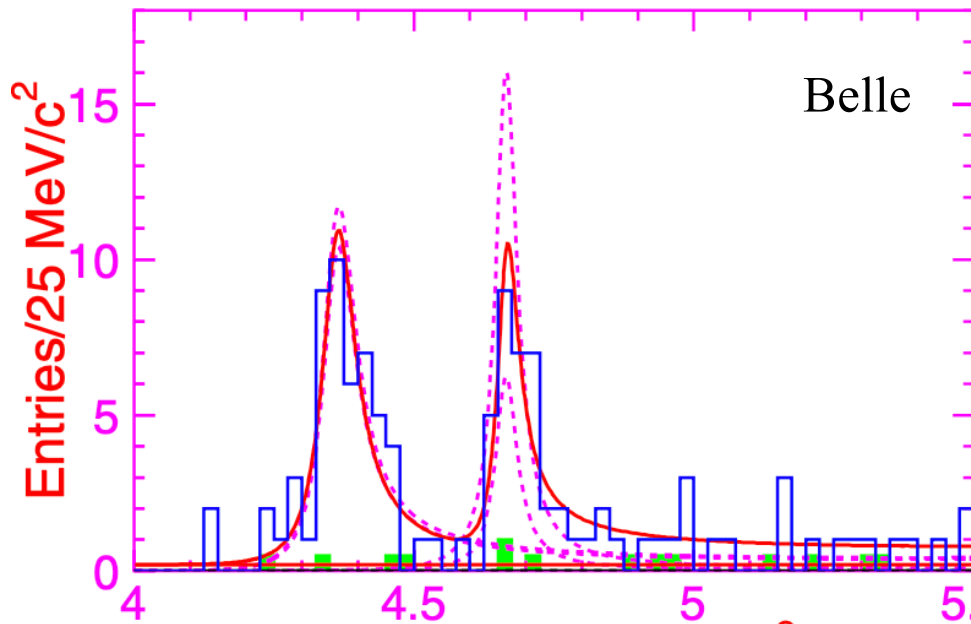
- Confirmation of the Y(4360) in $\psi(2S)\pi^-\pi^+$ with a significance of 8σ
- First observation of Y(4660) with 5.8σ

- BaBar confirms later the Y(4660)
- Further decay channels by Belle

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

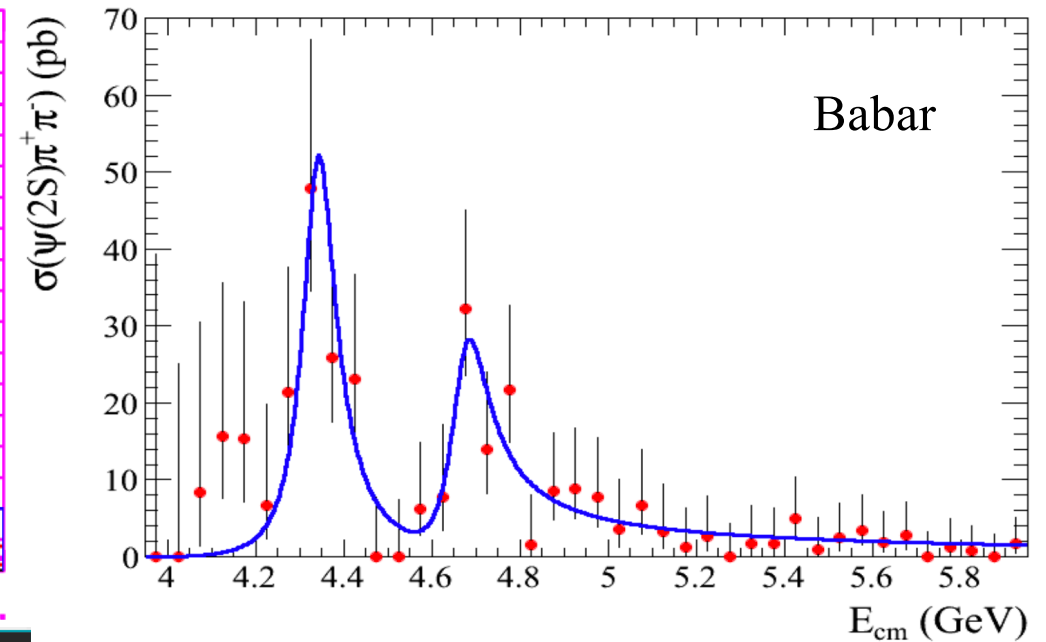
$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

[PRL 99, 142002 (2007)]



$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

[Phys. Rev. D 98, 111103 (2012)]

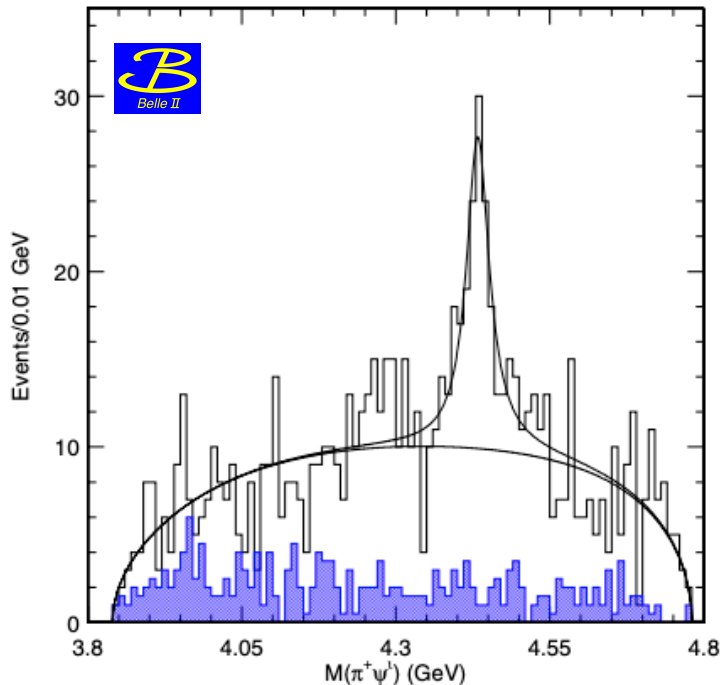


Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652\pm 10\pm 8$	$68\pm 11\pm 1$
BaBar, $\pi^+\pi^-\psi(2S)$	$4669\pm 21\pm 3$	$104\pm 48\pm 10$
Belle, $D_s^+D_{s1}(2536)^-$	$4626^{+7}_{-7} \pm 1$	$49.8^{+14}_{-12} \pm 4$
Belle, $D_s^+D_{s2}^*(2573)^-$	$4620^{+9}_{-8} \pm 3$	$47.0^{+32}_{-15} \pm 5$

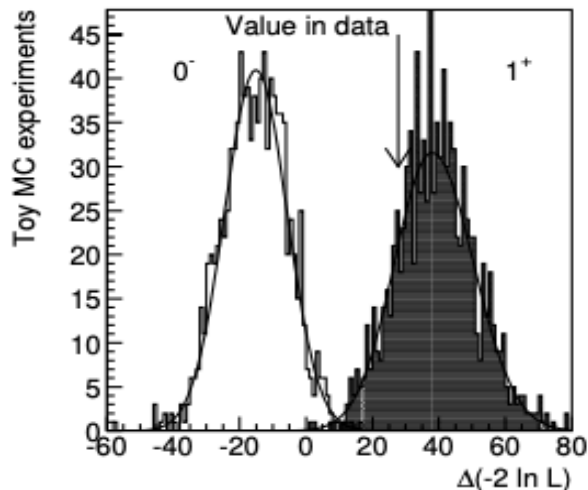
- BaBar confirms later the Y(4660)
- Further decay channels by Belle

The Z(4430) and further (charged) Zc states

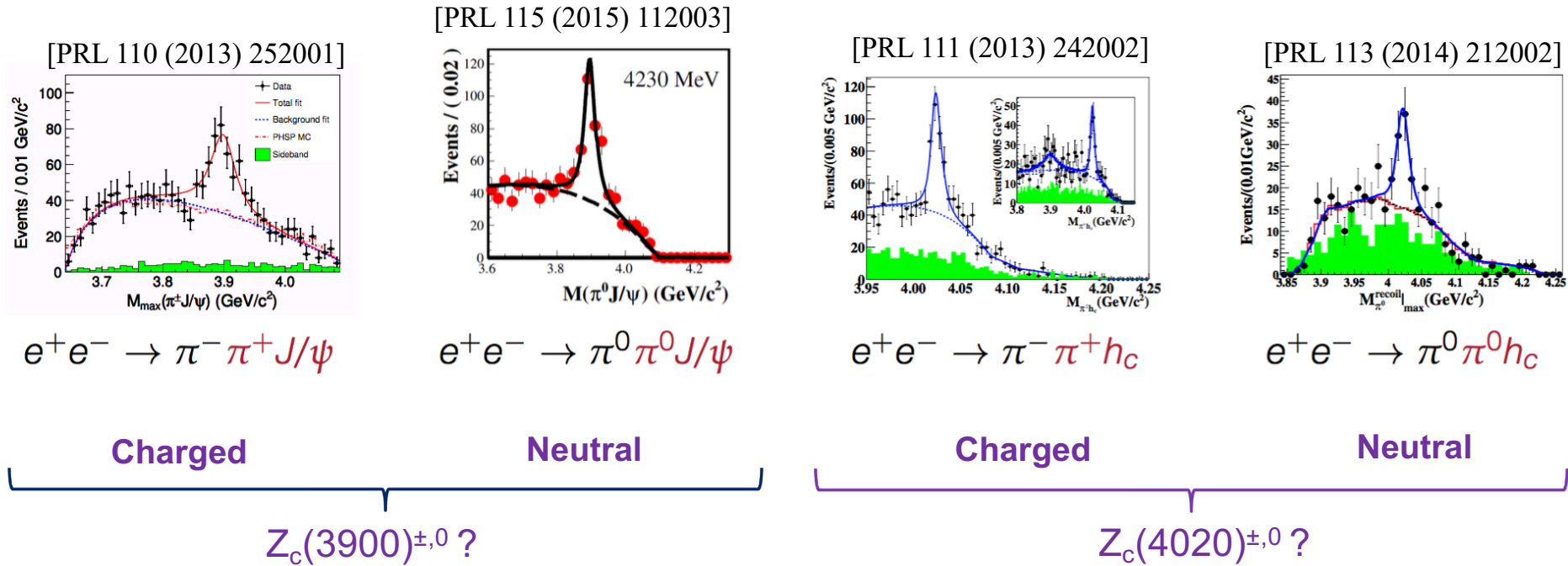
[Belle, Phys. Rev. Lett., 100 (2008) 142001]



[Belle, Phys. Rev. D 88 (2013) 074026]

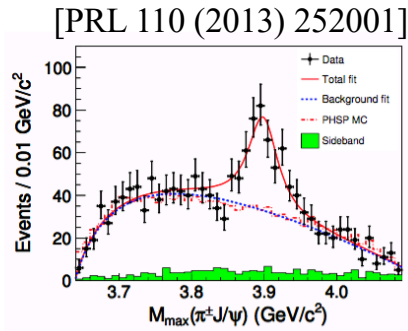


- First observed by Belle in 2008
 - $B \rightarrow K^\mp Z(4430)^\pm \rightarrow K^\mp \pi^\pm \psi'$
 - relatively narrow state, 6.5σ
 - first charmonium-like state with a non-zero electric charge
 => Minimal quark content $[c\bar{c}u\bar{d}]$ = manifestly exotic
- BaBar searched for it, however, does not confirm [PRD 79, 112001 (2009)]
- LHCb confirms and showed resonant behavior in argand plot [PRL 112, 222002 (2014)]
- Decay to $J/\psi/\pi$ seen in B decays by Belle [PRD 90, 112009 (2014)], and not seen by BaBar [PRD 79, 112001 (2009)]
- Spin-parity constrained by Belle: $J^P = 1^+$, confirmed by LHCb [PRL 112, 222002 & PRD 92, 112009 (2015)]



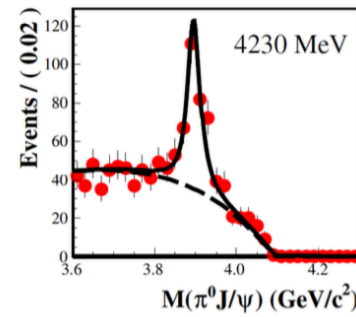
- Two isospin triplets of charmonium-like exotic states established

Hidden Charm



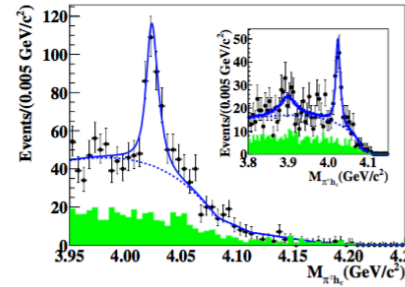
$$e^+e^- \rightarrow \pi^- \pi^+ J/\psi$$

[PRL 115 (2015) 112003]



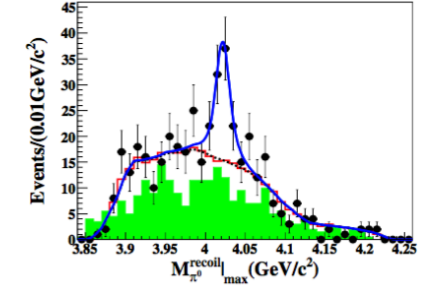
$$e^+e^- \rightarrow \pi^0 \pi^0 J/\psi$$

[PRL 111 (2013) 242002]



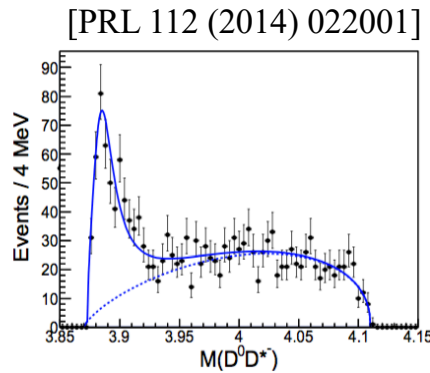
$$e^+e^- \rightarrow \pi^- \pi^+ h_c$$

[PRL 113 (2014) 212002]



$$e^+e^- \rightarrow \pi^0 \pi^0 h_c$$

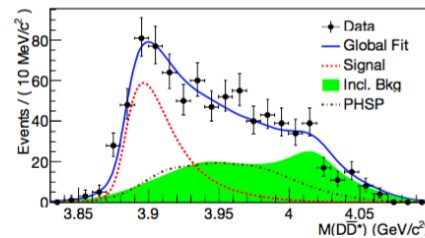
Open Charm



$$e^+e^- \rightarrow \pi^- (D\bar{D}^*)^+$$

Charged

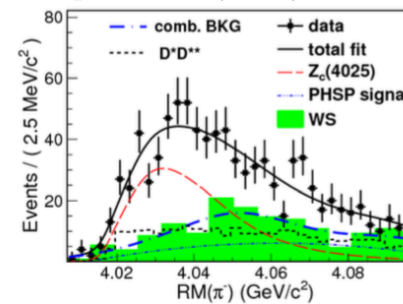
[PRL 115 (2015) 222002]



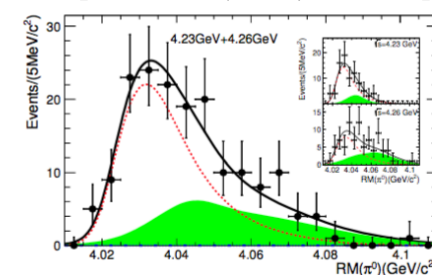
$$e^+e^- \rightarrow \pi^- (D^* \bar{D}^*)^+$$

Charged

[PRL 112 (2013) 132001]



[PRL 115 (2015) 182002]



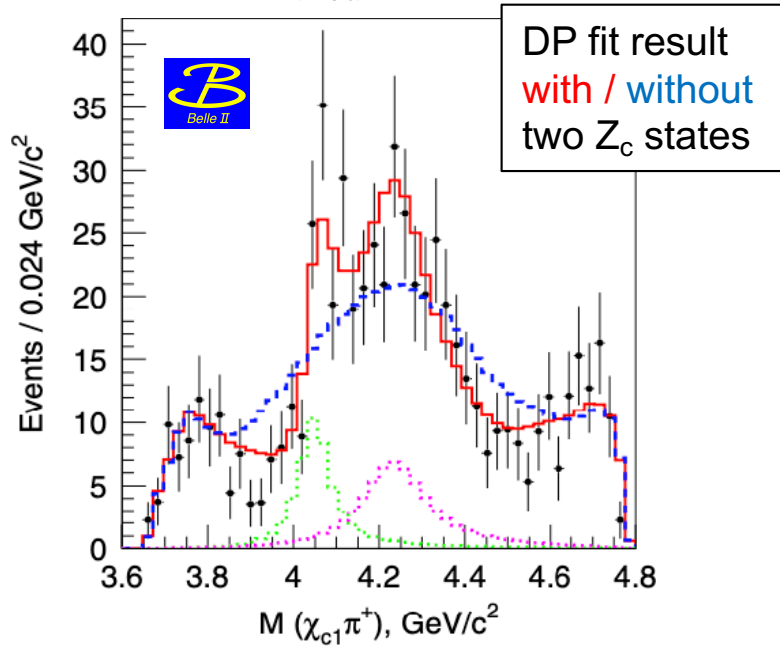
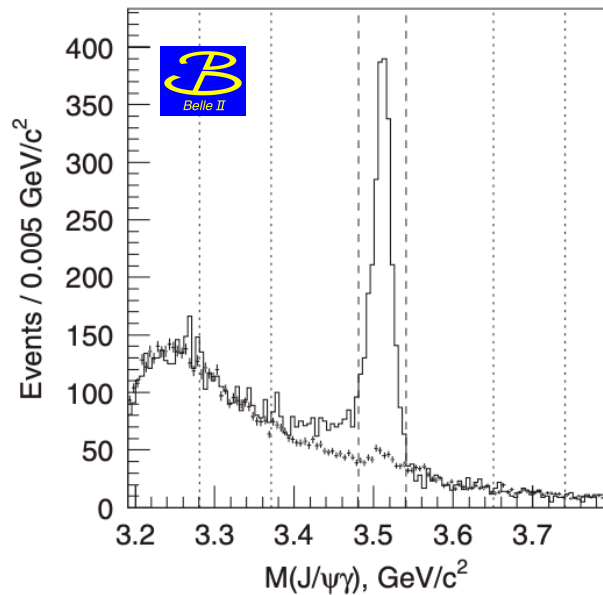
Neutral

$Z_c(3900)^{\pm,0} ?$

$Z_c(4020)^{\pm,0} ?$

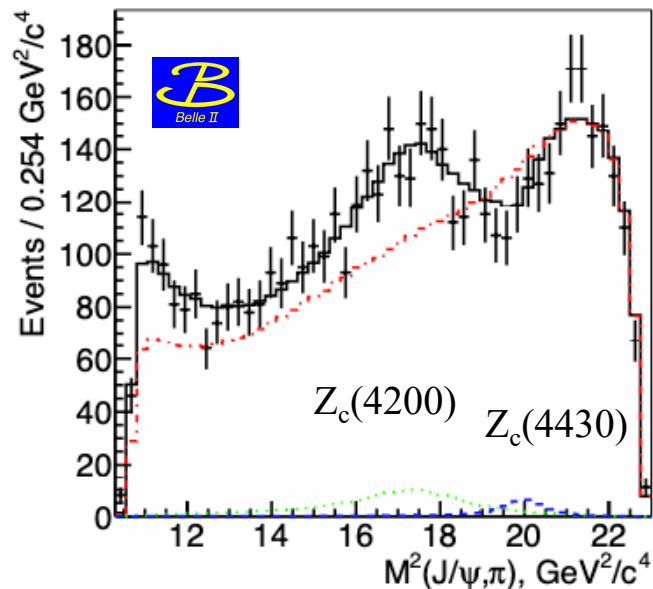
- Two isospin triplets of charmonium-like exotic states established
- Different decay modes (*hidden vs. open charm*) of same state observed?

[Belle, Phys. Rev. D 78 (2008) 072004]



- Two resonant structures in $\chi_{c1}\pi^+$ first observed by Belle in B decays, 2008
 - Dalitz plots analysis, each $> 5\sigma$
 - $M_1 = (4051 \pm 14^{+20}_{-41})\text{MeV}/c^2, \Gamma_1 = (82^{+21}_{-17}{}^{+47}_{-22})\text{MeV}$
 - $M_2 = (4248 \pm 14^{+44}_{-29}{}^{+180}_{-35})\text{MeV}/c^2, \Gamma_2 = (177^{+54}_{-39}{}^{+316}_{-61})\text{MeV}$
 - Similar to Z(4430) these are manifestly exotic charmonium-like candidates
 - With a non-zero electric charge
 - Thus, minimal quark content $\Rightarrow [c\bar{c}u\bar{d}]$
 - BaBar does not confirm [PRD 85, 052003 (2012)]
(accounting for $K\pi$ resonant structures $\Rightarrow 1\text{-}2\sigma$)
 - BESIII does not see the $Z_c(4050) \rightarrow \psi(3770)\pi^{+/-}$ [PRD 100, 032005 (2019)]
- \Rightarrow No confirmation yet, quantum numbers?
Neutral partners decaying to in $\chi_{c1}\pi^0$?

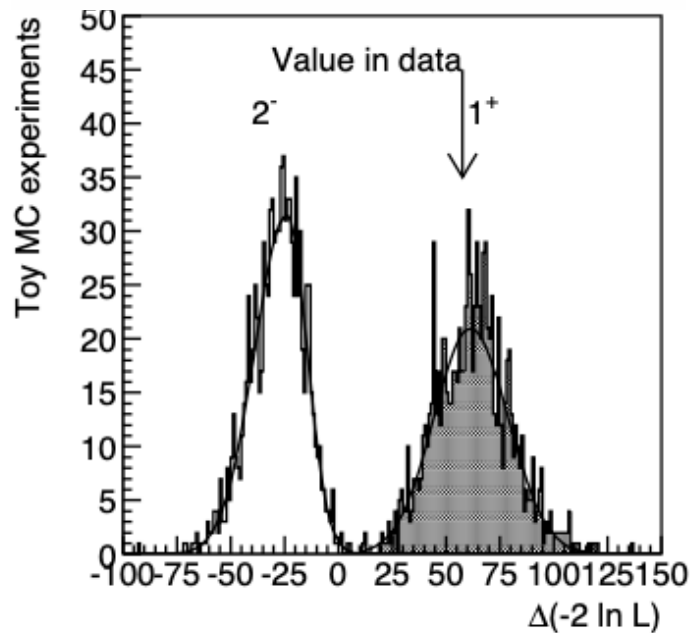
[Belle, Phys. Rev. D 90 (2014) 112009]



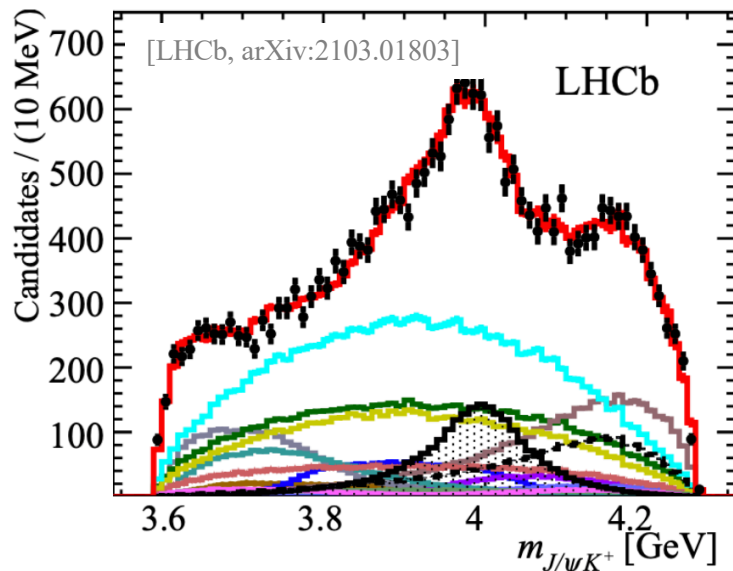
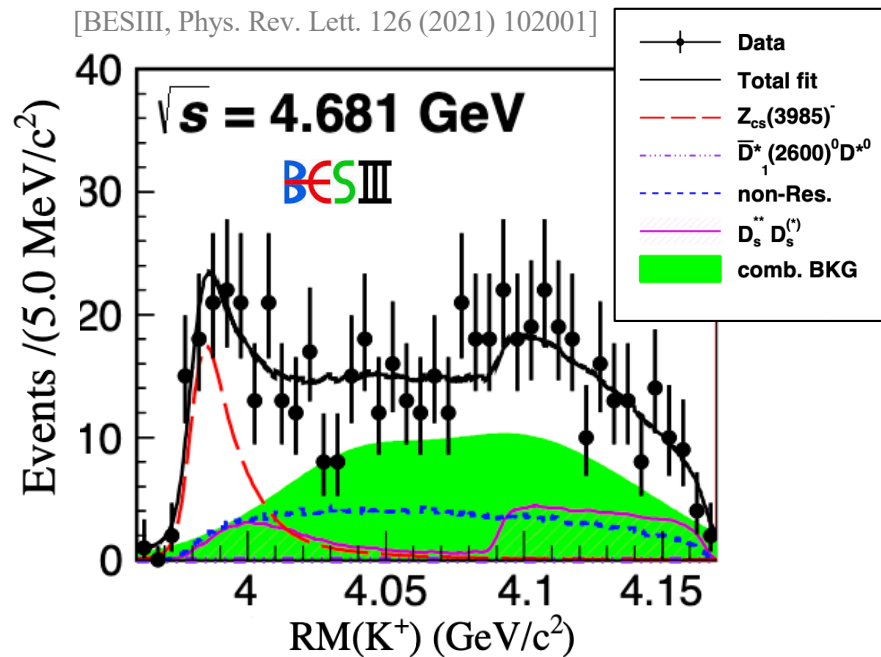
- New charged state decaying to $J/\psi\pi^+$ first observed by Belle in 2014 (711 fb⁻¹)
 - $\bar{B}^0 \rightarrow K^- J/\psi\pi^+$
 - Full amplitude analysis, 6.2σ significance
 - $M = (4196_{-29}^{+31} +_{-13}^{+17})\text{MeV}/c^2, \Gamma = (370_{-70}^{+70} +_{-132}^{+70})\text{MeV}$
 - $J^P = 1^+$ preferred over other hypotheses

- Evidence for $Z_c(4430) \rightarrow J/\psi\pi^+$ found

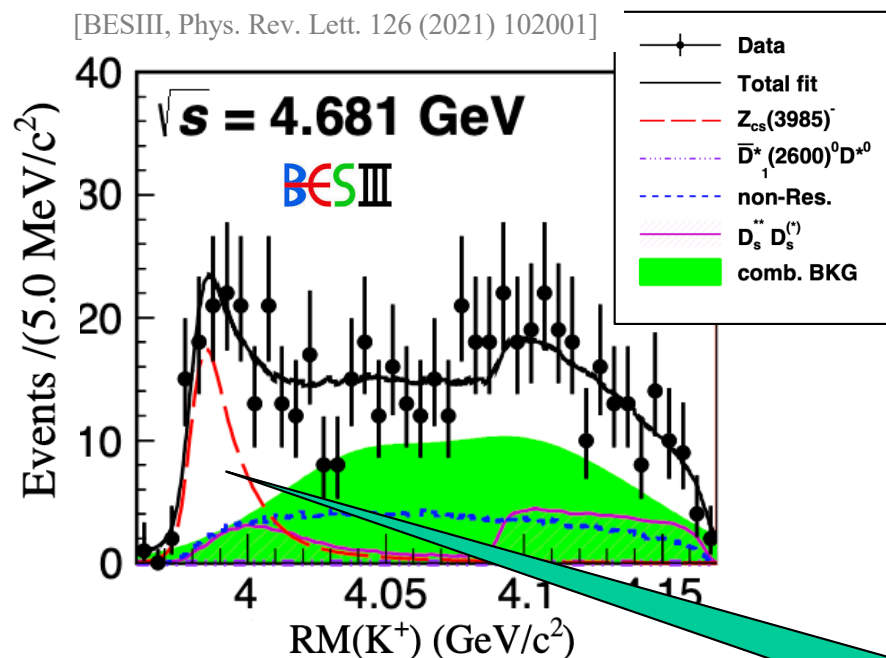
- Needs confirmation



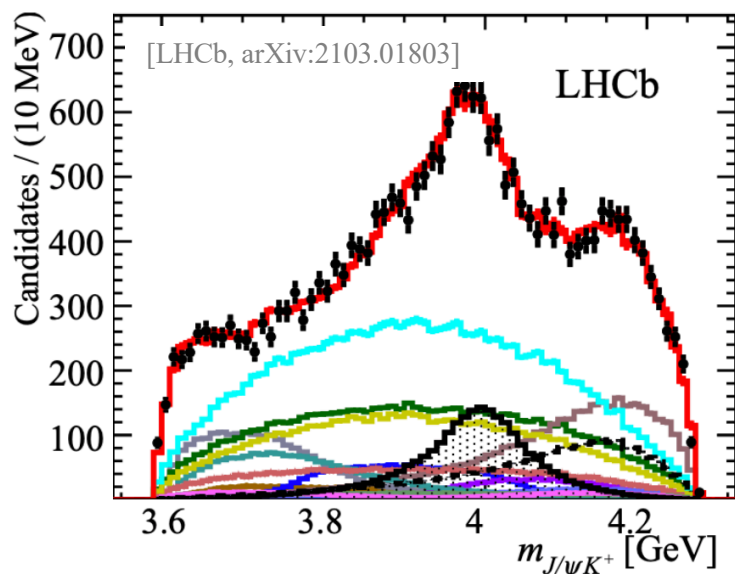
=> Further independent confirmation?
Neutral partners decaying to $J/\psi\pi^0$?



- Search for strange partner of $Z_c(3900)$
 - Containing s quark in open charm decay
 - $e^+e^- \rightarrow K^+(D_s D^*/D_s^* D)^-$
 - Narrow threshold enhancement (5.3σ)
 - $M = (3982.5^{+1.8}_{-2.6} \pm 2.1)\text{MeV}/c^2$,
 - $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0)\text{MeV}$
 - Manifestly exotic charged hidden-charm tetraquark candidate with strangeness
 - With a non-zero electric charge
 - Thus, minimal quark content $\Rightarrow [c\bar{c}s\bar{u}]$
 - LHCb reports a $Z_{cs}(4000)$ in $B \rightarrow \phi(J/\psi K^+)$
 - $M = (4000.3 \pm 6^{+4}_{-14})\text{MeV}/c^2$,
 - $\Gamma = (131 \pm 15 \pm 26)\text{MeV}$
 - $J^P = 1^+$, hidden charm final state
 - 10x broader ...
- \Rightarrow Same state observed in different decays (open/hidden charm) at two experiments?



- Search for strange partner of $Z_c(3900)$
 - Containing s quark in open charm decay
 - $e^+e^- \rightarrow K^+(D_s D^*/D_s^* D)^-$
 - Narrow threshold enhancement (5.3σ)
 - $M = (3982.5_{-2.6}^{+1.8} \pm 2.1) \text{ MeV}/c^2$,
 - $\Gamma = (12.8_{-4.4}^{+5.3} \pm 3.0) \text{ MeV}$
- Manifestly exotic charged hidden-charm tetraquark candidate with strangeness
 - With a non-zero electric charge
 - Thus, minimal quark content $\Rightarrow [c\bar{c}s\bar{u}]$

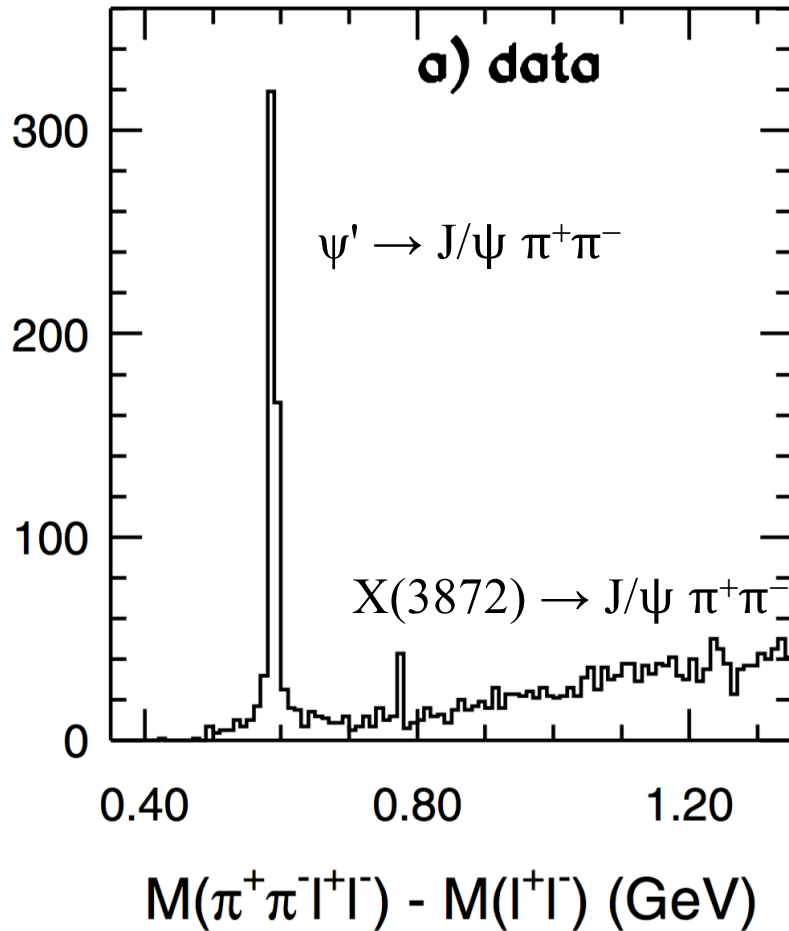


For details, see previous BESIII talk by M. Pelizaeus → $\phi(J/\psi K^+)$

- $J = 1$, hidden charm final state
 - 10x broader ...
- \Rightarrow Same state observed in different decays (open/hidden charm) at two experiments?

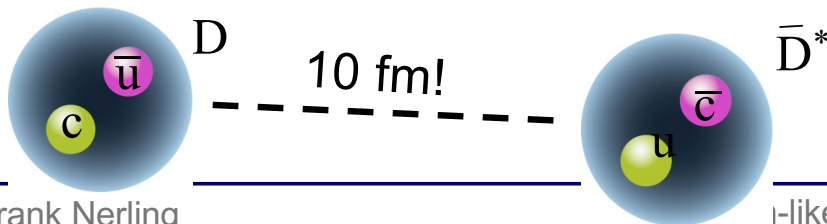
The X(3872) and further X states

[Belle Collab., PRL 91 (2003) 262001]



- First observed by Belle in 2003
 - $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
 - very narrow state with $J^{PC} = 1^{++}$
- Belle & BaBar report signal in
 - $X(3872) \rightarrow D^0 \bar{D}^{*0}$
- Mass $m[X(3872)] - m[D^{*0}] - m[D^0]$
 $= (-0.07 \pm 0.12) \text{ MeV}/c^2$ (LHCb 2020)
- Width measurement:
 - $\Gamma_{X(3872)} < 1.2 \text{ MeV}$ (2011, Belle)
 - $\Gamma_{X(3872)} = 1.13 \text{ MeV}$ (2020, LHCb)

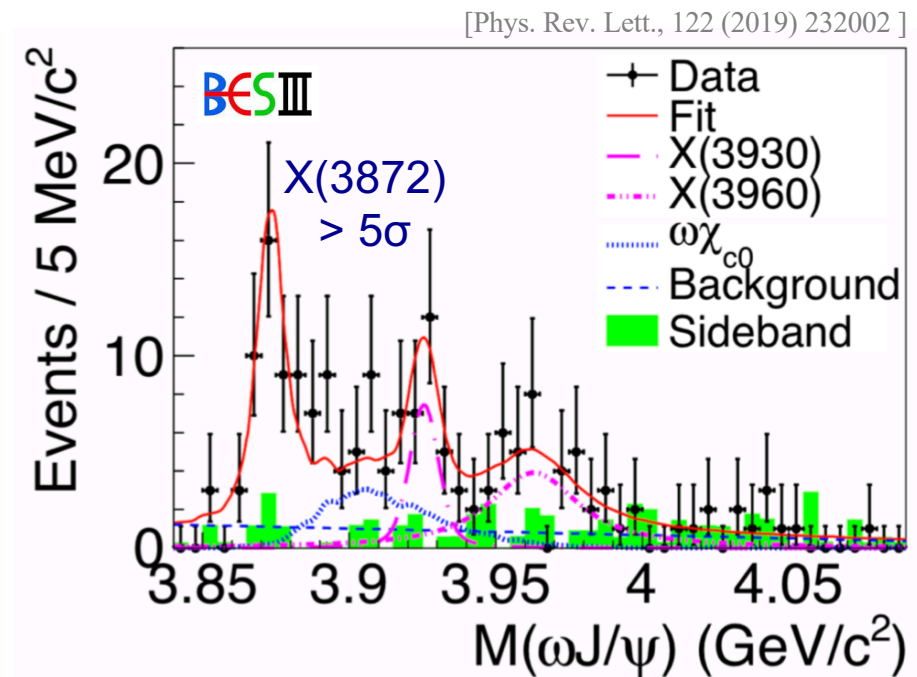
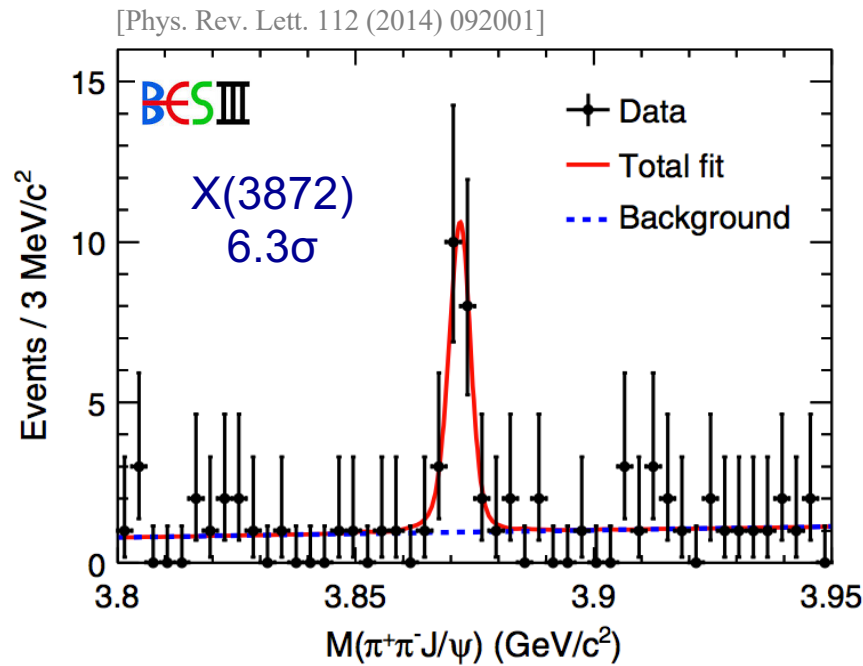
Analogy to deuteron:



For clarification:

=> Precision measurement with sub-MeV resolution needed!

BESIII: First observation of $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+ \pi^- J/\psi$
First observation of $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \omega J/\psi$

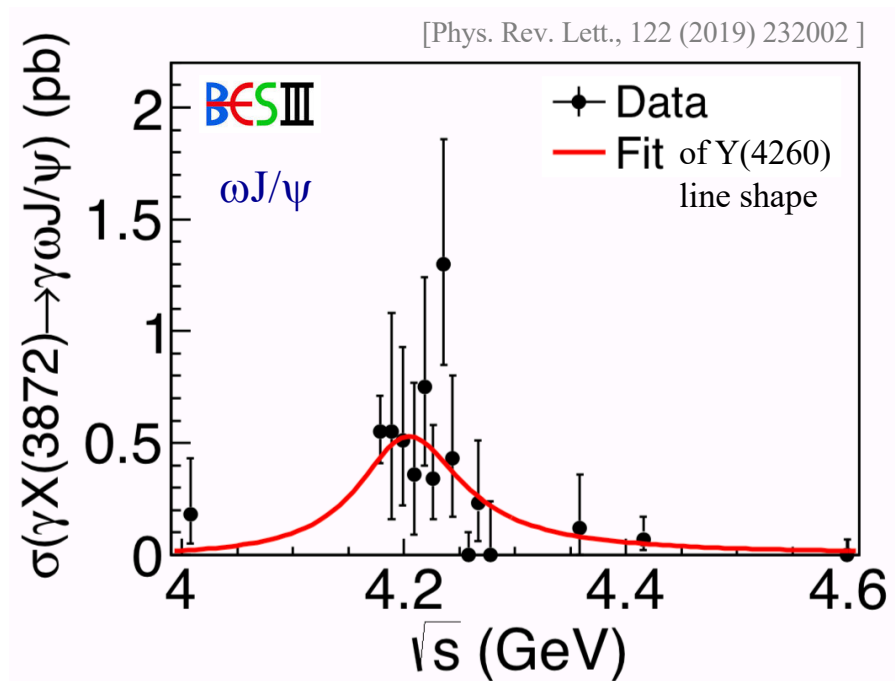
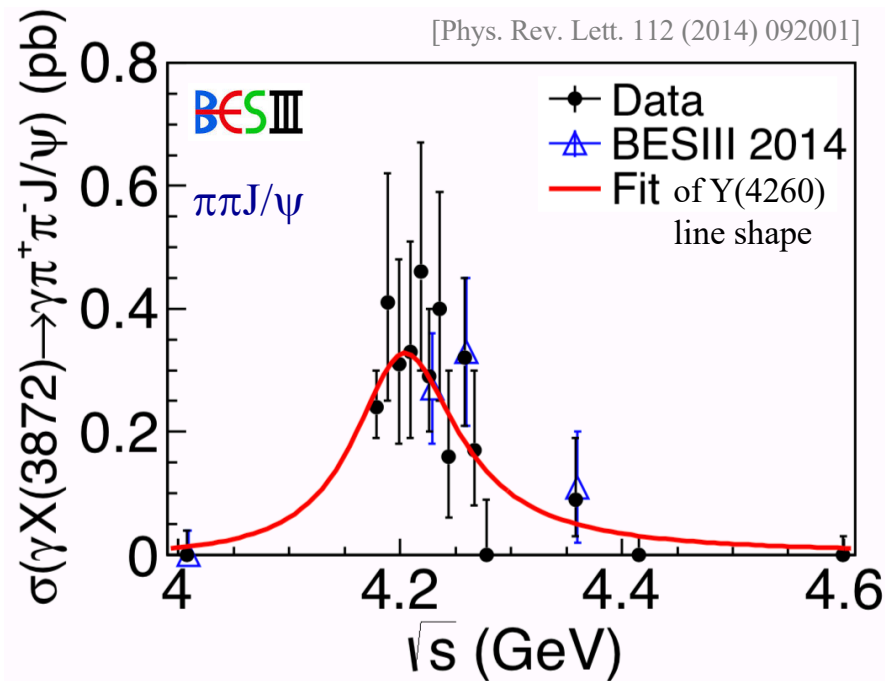


- $m = (3871.9 \pm 0.7 \pm 0.2) \text{ MeV}/c^2$
- $\Gamma < 2.4 \text{ MeV}$ (90% CL)

- Fit with three Breit-Wigner resonances
 => Evidence for two more structures

BESIII: First observation of $e^+e^- \rightarrow Y(4260) \rightarrow \gamma X(3872) \rightarrow \gamma\omega J/\psi$
 First observation of $e^+e^- \rightarrow Y(4260) \rightarrow \gamma X(3872) \rightarrow \gamma\pi^+\pi^- J/\psi$

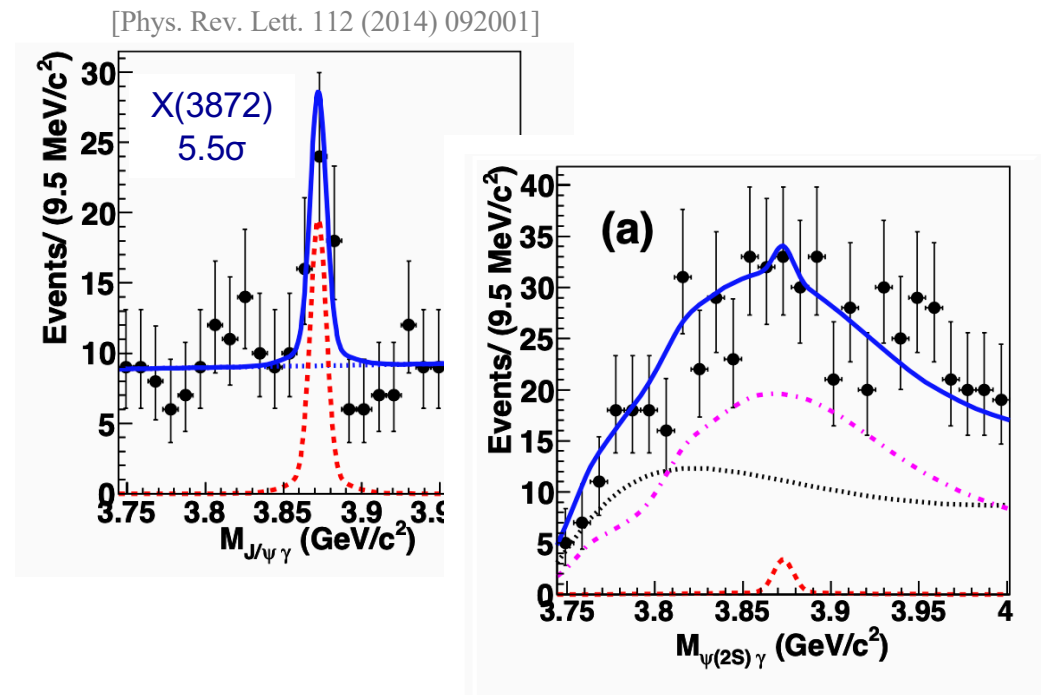
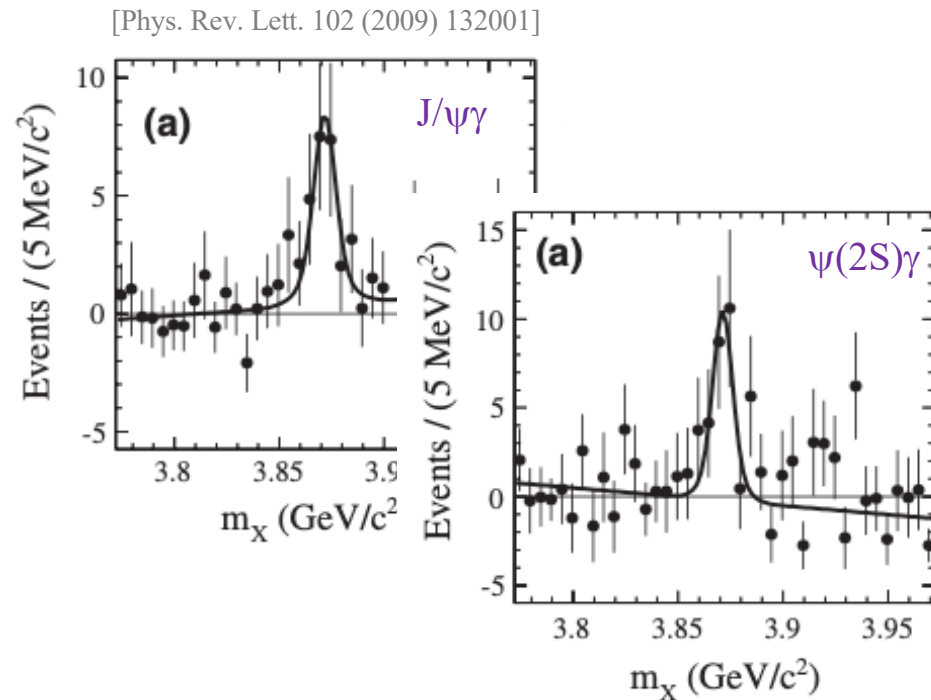
cross section



- $m = (4200.6^{+7.9}_{-13.3} \pm 3.0) \text{ MeV}/c^2$
- $\Gamma = (115^{+38}_{-26} \pm 12) \text{ MeV}/c^2$

- Shape consistent with production via a Y(4260) state

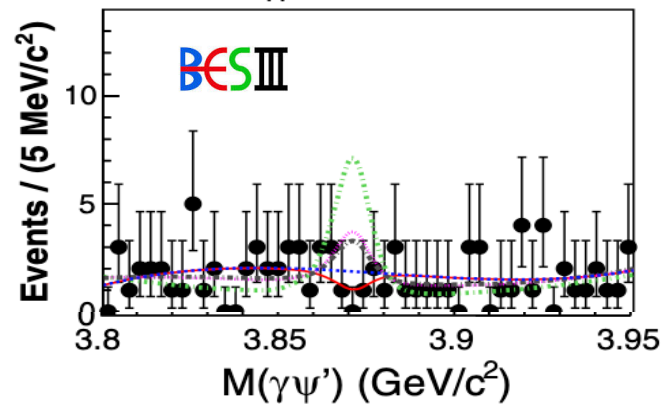
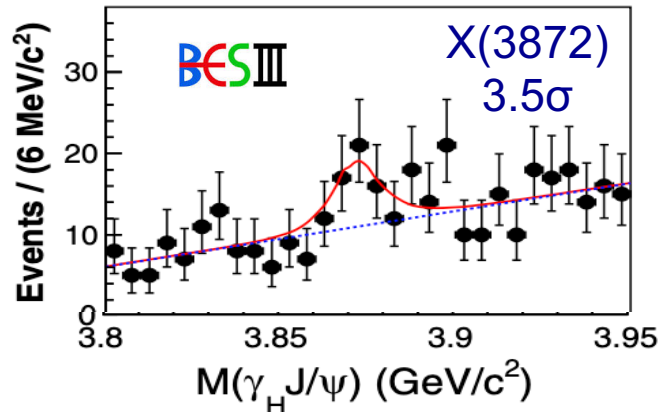
Belle: First observation of $B \rightarrow K X(3872)$, with $X(3872) \rightarrow J/\psi\gamma$
 And **no evidence** for $B \rightarrow K X(3872)$, with $X(3872) \rightarrow \psi(2S)\gamma$



- BaBar reported evidence for both, $J/\psi\gamma$ and $\psi(2S)\gamma$ with significances of 3.6σ and 3.5σ , respectively

- Belle observes the $J/\psi\gamma$ decay ($>5\sigma$) but no evidence for $\psi(2S)\gamma$
- Non-observation contradicts BaBar's constraint against pure $D^*\bar{D}$ molecular interpretation [PRL 102, 132001 (2009)]

[Phys. Rev. Lett., 124 (2020) 242001]



Molecule vs. Tetraquark?

$$\frac{B[X(3872) \rightarrow \gamma \psi(2S)]}{B[X(3872) \rightarrow \gamma J/\psi]} < 0.59 \text{ (BESIII) @ 90\% C.L.}$$

$$< 2.1 \text{ (Belle) @ 90\% C.L.}$$

PRL 107, 091803 (Belle)
PRL 102, 132001 (BaBar)
NPB 886(665) (LHCb)

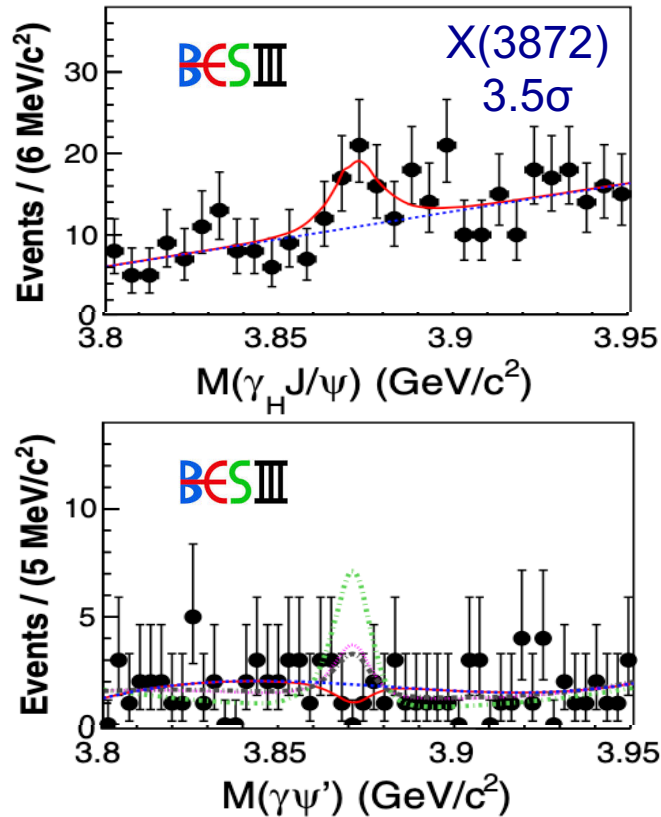
$$= 3.4 \pm 1.4 \text{ (BaBar)}$$

$$= 2.46 \pm 0.64 \pm 0.29 \text{ (LHCb)}$$

- BESIII: Radiative decays of X(3872)
 - Evidence for $X(3872) \rightarrow \gamma J/\psi$ (3.5σ),
 - No obvious signal for decay to $\gamma \psi'$

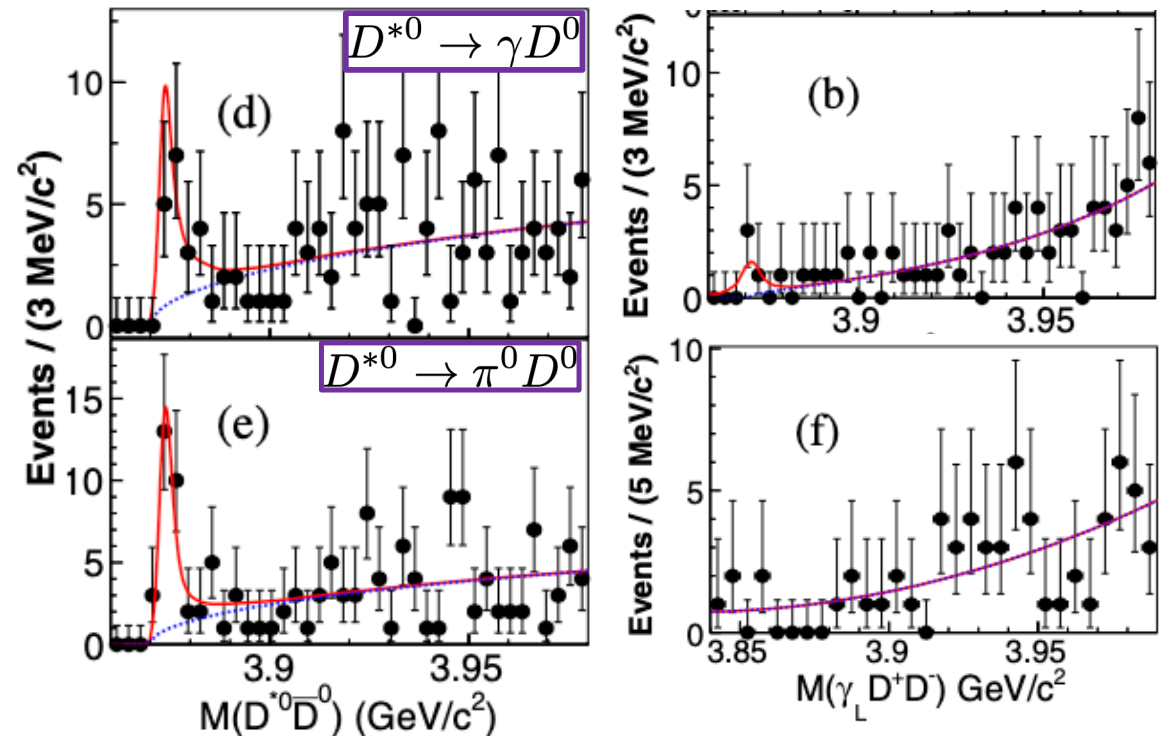
=> Essential input to future tests of the molecular interpretation of X(3872)?

[Phys. Rev. Lett., 124 (2020) 242001]



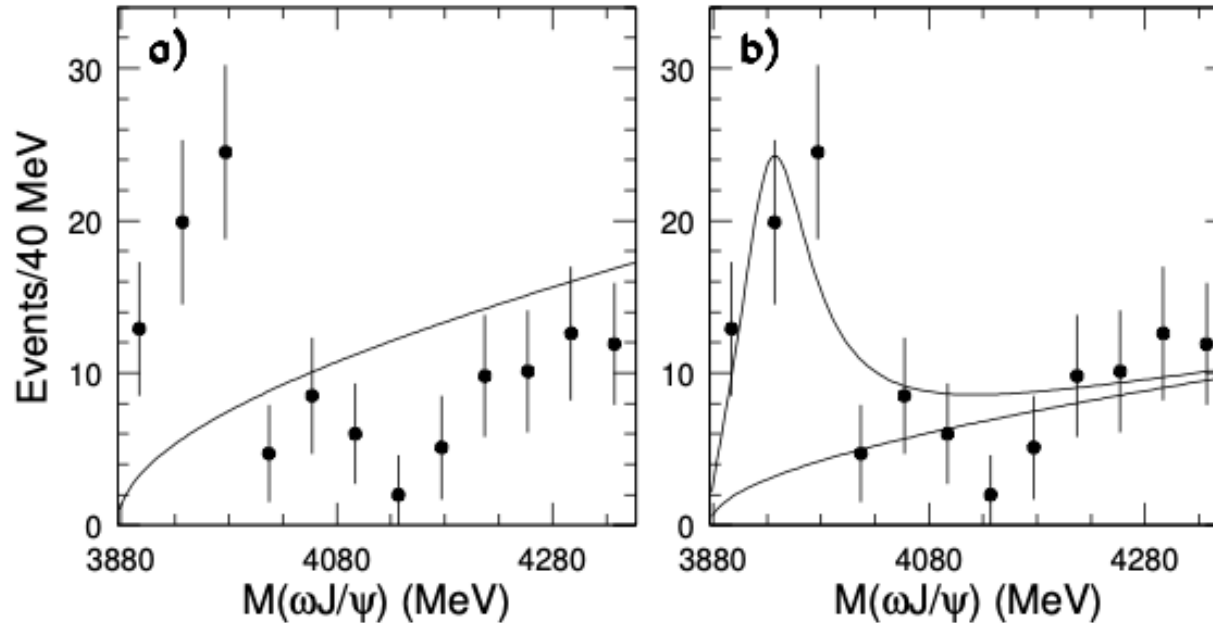
- BESIII: Radiative decays of X(3872)
 - Evidence for $X(3872) \rightarrow \gamma J/\psi$ (3.5σ),
 - No obvious signal for decay to $\gamma \psi'$

[Phys. Rev. Lett., 124 (2020) 242001]



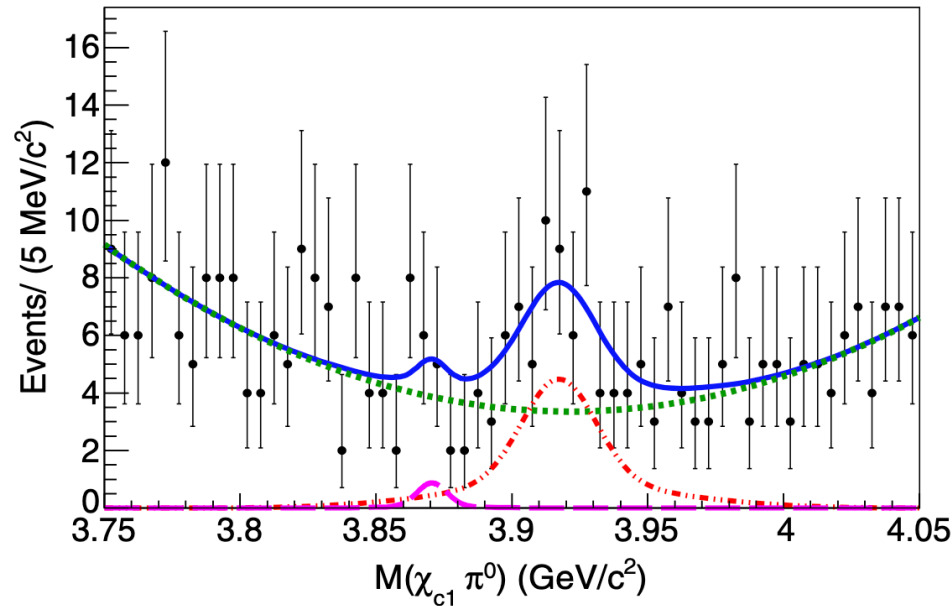
- BESIII: $X(3872) \rightarrow D^{*0} \bar{D}^0 + \text{c.c.}$ (7.4σ)
 - No obvious signal for decay to $\gamma D^+ D^-$
 - Open charm decay dominant

[Belle, Phys. Lett. 94, 182002 (2005)]

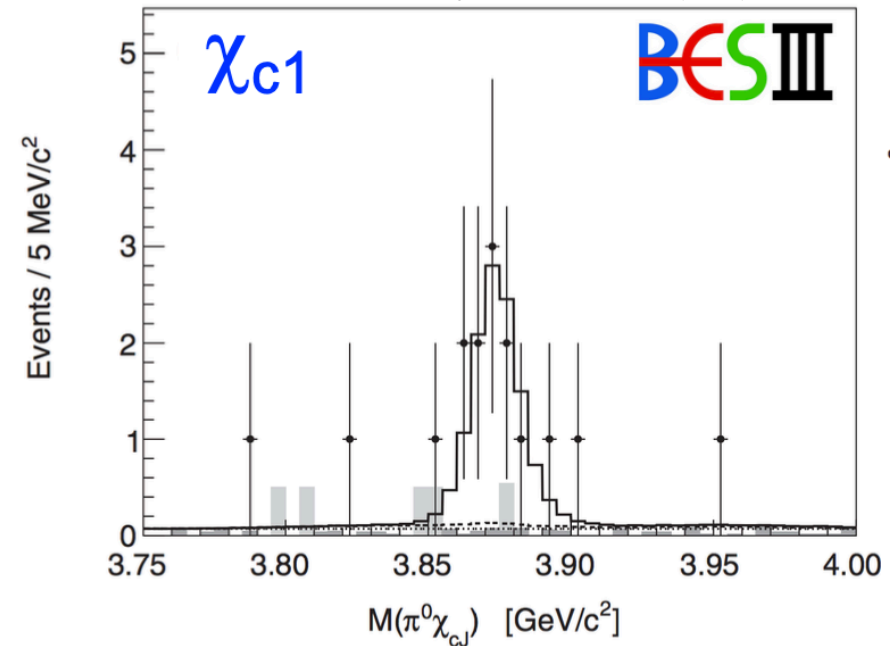


- The X(3915) has been observed by Belle in B decays, $X(3915) \rightarrow \omega J/\psi$ (NB: initially named Y(3940))
- Confirmation in B decays by BaBar [PRD 82, 011101 (2010)]
- Also observed in $\gamma\gamma \rightarrow \omega J/\psi$ by Belle [PRL 104, 092001 (2010)] and BaBar [PRD 86, 072002 (2012)]

[Belle, Phys. Rev. D 99 111101 (2019)]



[BESIII, Phys. Rev. Lett., 122 (2019) 202001]



- No significant signals were found by Belle in search for $X(3872)$ and $X(3915)$ to $\chi_{c0} \pi^0$ ($0.3\sigma / 2.3\sigma$)
 - $B(X(3872) \rightarrow \chi_{c1} \pi^0) / B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) < 0.97$ (90% C.L.)
- BESIII observes now $X(3872)$ decay to $\chi_{c0} \pi^0$ ($> 5\sigma$)
 - $B(X(3872) \rightarrow \chi_{c1} \pi^0) / B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = 0.88^{+0.33}_{-0.27} \pm 0.10$.

Isospin violation,
comparable decay
rate to $J/\psi \rho$

=> Disfavours $\chi_{c1}(2P)$

- New era of charmonium-like states started two decades ago, and more than 20 unexpected XYZ states have been discovered
 - Supernumerary vector Y states consistently resolved (statistics)
 - $Y(4260)$ and $Y(3360) \rightarrow Y(4220), Y(4390)?$
 - First *decays to open charm*, further *new decay modes to $c\bar{c}$ and/or light hadrons* investigated
 - More *candidates reported*, especially $Y(4660)$ to be studied (confirmed)
 - Charged Z_c states are manifestly exotic states
 - First complete *isospin triplets established*
 - First *strange partner(s)* reported
 - More *candidates reported*, further to be studied (confirmed)
 - The first of these states discovered, the $X(3872)$ still not understood
 - Consistent picture in *B decays and e^+e^- production*
 - *Line shape* to be measured precisely
 - More *candidates reported*, further to be studied (confirmed)
- Different states observed in B decays vs. e^+e^- annihilation

- The B factories CLEO(-c) and BarBar have run for one / two decades
- Belle has run a decade, meanwhile upgraded to BelleII
 - Comissioned, first physics run last year
 - Looking forward to new results
- BESIII successfully operating since 2008
 - World largest data sets in tau-charm mass region, unique XYZ data
 - Machine upgrade allows to extend studies up to $E_{\text{cms}} = 5 \text{ GeV}$
- Upcoming and future experiments
 - PANDA/FAIR as complementary and unique $p\bar{p}$ experiment
 - Super tau-charm factory in China and/or Russia

Outlook

- Completion of the exotic multiplets
 - *High **statistics** and **precision**, in combination with **different probes***